Application of Automatic Vehicle Location In Law Enforcement

—An Introductory Planning Guide

32263

National Criminal Justice Information and Statistics Service
Law Enforcement Assistance Administration
United States Department of Justice

Application of Automatic Vehicle Location In Law Enforcement

—An Introductory Planning Guide

G.R. Hansen
W.G. Leflang

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California 91103

September 1978

National Criminal Justice Information and Statistics Service
Law Enforcement Assistance Administration
United States Department of Justice

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

Stock Number 027-000-00746-5

U.S. DEPARTMENT OF JUSTICE
Law Enforcement Assistance Administration

James M. H. Gregg, Acting Administrator

Harry Bratt, Assistant Administrator
National Criminal Justice Information
and Statistics Service

Wayne P. Holtzman, Director
Systems Development Division

This document presents results of work supported by the Law Enforcement Assistance Administration, U.S. Department of Justice, under the Omnibus Crime Control and Safe Streets Act of 1968, as amended. It was sponsored under an inter-agency agreement with the National Aeronautics and Space Administration through Contract NAS 7-100. Points of view or opinions stated in this document are those of the authors and do not necessarily represent the official position of the U.S. Department of Justice.

FOREWORD

This book has been prepared and distributed to provide public safety planning personnel with a compact source of information on one of the most important aspects of police command and control, automation, namely automatic vehicle location (AVL) systems. An AVL system is valuable for the improvements it provides in the critical dispatching function, and can enhance officer safety as well as provide essential data for the improvement of patrol operations.

This volume is one of a series prepared under the sponsorship of the Law Enforcement Assistance Administration (LEAA) to provide planning guidelines on the various aspects of police command and control automation. The complete series consists of the following documents:

Title	Document No.
Application of Mobile Digital Communications in Law Enforcement	JPL SP43-6 Rev. 1
Application of Computer-Aided Dispatch in Law Enforcement	JPL 5040-16
Application of Automatic Vehicle Location in Law Enforcement	JPL 5040-17
Patrol Force Allocation in Law Enforcement	JPL 5040-18
Multijurisdictional Command and Control Systems in Law Enforcement	JPL 5040-19

The series was prepared by the Jet Propulsion Laboratory of the California Institute of Technology, using the results of studies sponsored by LEAA at JPL as well as at other institutions. The documents are being distributed as part of LEAA's mission of giving technical assistance to state and local law enforcement agencies. They are addressed to the local law enforcement planner who must face practical working problems in deciding what degree and kind of automation best suits his department. Our intention has been to give him the basic understanding he needs to make such a decision, and procedures for making the associated analyses or having them made. The manuals are developed within the framework of the overall command and control system so that potential benefits of individual innovations can be evaluated in terms of improved system performance.

The technologies that are available to law enforcement agencies today have the promise of making their operations more efficient as well as more effective. Our hope is that this series of documents will provide a clear and concise picture of what that promise is and what is involved in making it a reality.

S. S. Ashton, Jr.
Systems Development Division
National Criminal Justice
Information and Statistics Service
Law Enforcement Assistance Administration
United States Department of Justice

CONTENTS

CONTENTS (Continued)

CONTENTS (Continued)

FIGURES

ABSTRACT

A set of planning guidelines for the application of automatic vehicle location (AVL) to law enforcement is presented. Some essential characteristics and applications of AVL are outlined; systems in the operational or planning phases are discussed. Requirements analysis, system concept design, implementation planning, and performance and cost modeling are described and demonstrated with numerous examples. A detailed description of a typical law enforcement AVL system, and a list of vendor sources are given in appendixes.

This document is one of a series of five guideline manuals on mobile digital communications, computer-aided dispatch, automatic vehicle location, patrol force allocation, and multijurisdictional command and control systems for law enforcement applications.

1. INTRODUCTION

1.1 The Growing Interest in Automatic Vehicle Location

Automatic vehicle location (AVL) systems, sometimes called automatic vehicle monitoring systems, are beginning to receive interest in the law enforcement community and from operators of vehicle fleets such as bus lines, taxicab companies, and truck lines. The U.S. Department of Justice, the U.S. Department of Transportation, and the U.S. Department of Housing and Urban Development have supported studies, demonstration tests and, in some cases, installation of working systems in cities. The Law Enforcement Assistance Administration of the Department of Justice has a strong interest in AVL systems because of the potential benefits to law enforcement agencies. In its volume on police, the National Advisory Commission on Criminal Justice Standards and Goals recommends (item 23.1) that the LEAA stimulate the development of a digital communication system which includes, as a minimum, automated vehicle locater devices as well as other status reporting and display devices (Ref. 1).

Law enforcement interest in AVL systems stems from the rapid and accurate car location information provided to dispatching and police supervisory personnel. This information provides the ability to deploy patrol cars in such a way as to reduce the police response time to the scene of a crime, improve coordination of police activities, better supervise officers' daily actions, and improve officer safety by monitoring the location of patrol cars. All this is done without the need for location reporting by voice, thus reducing the work load of both the field officer and dispatcher, and reducing congestion on the crowded voice radio channels.

On the other hand, there are some drawbacks to an AVL system. System costs are relatively high. Additional specialized equipment must be maintained. Some systems use a large amount of the radio frequency spectrum. It is difficult to show a dollars-and-cents benefit to AVL since one of its primary features is officer safety – a nonmonetary value. As yet, too little experience has been gained to demonstrate the magnitude of AVL's contribution to officer safety. R.D. Doering, in a study for the City of Orlando, showed that 34 patrol cars with AVL could achieve the same response time as 35.8 cars without AVL. Thus, a cost savings can be identified. However, weighing all the advantages and disadvantages of an AVL system is difficult and is the challenge confronting the planner.

1.2 Status of Automatic Vehicle Location

Three different types of AVL are currently being proposed and tested:

(1) Dead reckoning.

(2) Proximity.

(3) Radiolocation.

Each of these will be described in detail in Chapter 2.

The Boeing Company and E-Systems, Inc. have both developed magnetic-compass odometer dead-reckoning systems. Proximity systems include an X-band signpost by RCA, a Citizens Band signpost by Hoffman Electronics, and a buried magnet system by Novatek, Inc. Other proximity systems have been installed, such as the Chicago Transit Authority system by Motorola, a bus line system in Hamburg, Germany by Philips of Eindhoven, and the LOCATES system for the Montclair, California, Police Department. Radiolocation systems have been demonstrated by the Sierra Research Corp. with a narrow-band FM phase system, and the Cubic Corp. with a wide-band FM phase system. Hazeltine Corp. has tested the pulse time-of-arrival technique and Raytheon Corp. has also demonstrated an FM phase system. The Loran system techniques are currently being advocated by the Teledyne Corp.

Most of the systems mentioned have only been tested under controlled conditions. Relatively few have been actually installed in cities and used in day-to-day operations by law enforcement or other agencies. Thus, there is very little factual data regarding the performance of the various systems in use. A system which may be best for a low rise, largely suburban city may not be best for a high rise urban city with dense population. A mountainous or hilly city presents communication problems to some AVL systems but not to others. Although the foundations of AVL systems are not new, their application to law enforcement vehicles in a city presents new problems to the designer. Field experience over the next several years should narrow the range of competing systems but the agency planners are still faced with a bewildering array of claims for systems for which the cost is, unfortunately, not small.

1.3 The Guidelines Manual

The purpose of this introductory guidelines document is to assist law enforcement agencies in understanding, planning for, and implementing AVL systems. The chapter on selection of system design (Chapter 4) presents several concepts for typical cities. The appendix provides a list of vendor contacts from which the agency planner may obtain details on specific systems.

2. AUTOMATIC VEHICLE LOCATION FOR LAW ENFORCEMENT

2.1 Applications of Automatic Vehicle Location

There are a variety of law enforcement applications that can be served by AVL systems. The ability of the system to present an accurate view of the location of all or a small part of the fleet will determine how well the many applications can be realized. Those techniques which provide continuous and current location information will find the widest application; those techniques which can only accurately locate a few vehicles at a time will not provide the information required for all applications.

All automatic vehicle location techniques can keep track of all the vehicles in a fleet. Some techniques perform this function rapidly and all data is reasonably current. Other techniques require considerable time to survey an entire fleet, and the location data is usually too old to be of value; a new inquiry must be made if an accurate location of a particular unit is required.

2.1.1 Dispatching

Providing the dispatcher with the location of the vehicles under his control is one of the primary justifications for the use of AVL. It is expected that the time required to respond to calls for service will be reduced as a result of improved dispatcher information. The reduction in response time is determined by the accuracy of the location system and the dispatching philosophy used.

The magnitude of the response time reduction has been predicted by various investigators, but never verified through before and after measurements. It can be reasoned that the greatest overall reductions will occur with an AVL system with perfect accuracy and a dispatching philosophy of always sending the closest car to an incident. Any errors in the location will result in some "wrong" dispatches where the closest car is not sent, but rather some other car which must travel farther and longer. As the error in location increases, the number of "wrong" dispatches increases until the dispatching performance with AVL is the same as without.

A maximum 7 to 14% reduction in average response time has been estimated for a perfect location system. The improvement slowly diminishes as the error in location increases and there is minimal improvement when the error is about two-thirds the side of the area patrolled by any one vehicle.

If the dispatching rule is to always send the beat vehicle to any incident in the beat, there is little if any improvement in response time to be gained through AVL. A small improvement is to be expected if the closest adjacent car is dispatched when the beat car is busy. A larger improvement results when adjacent beat vehicles are always dispatched if they are closer than the beat vehicle.

Dispatching of the closest car regardless of beat assignment very quickly results in a large percentage of the vehicles being out of their beat for a substantial period of time. In fact, cars may be out of their assigned beats in direct proportion to the time spent answering calls. Adjacent beat assigning can also result in a substantial number of cars being out of beat. In slack periods, most cars will be in the proper beat and available. Under these circumstances AVL will not appreciably diminish response time. Similarly, under conditions where most cars are busy, AVL location data is redundant as the dispatcher knows where the car is by the assignment. The utilization factors where AVL has the greatest effect for response time improvement are between 30 and 70 percent, but the differences are not large.

2.1.2 Tactical Control

Officer-initiated actions such as hot pursuit can be aided substantially by timely, accurate location information. Location of the pursuing unit by means of AVL will relieve the officers of frequent voice reports, and should allow the dispatcher to determine intercept locations for other units. Similarly, in encirclements, tactical blocking of escape routes, or perimeter control the AVL system will provide the watch commander with current locations of units so that rapid decisions can be made regarding deployment.

Civil strife and natural disasters are occurrences where location knowledge of the entire fleet should prove extremely valuable, although the effect of natural disasters on the location equipment must be considered. Widespread power failures or interrupted data links will render some AVL techniques useless for location purposes, while others will be slightly affected.

Tactical control requires current knowledge of unit locations, and the interrogation technique has a very important influence on the speed and flexibility of location reporting. Another consideration is the integration of other emergency public service users of the AVL system. Techniques which allow great independence among users are least affected while systems which use a centralized location determination service are more affected by the concentrated use during large scale emergencies.

2.1.3 Officer Safety

Knowledge of the location of all units should be particularly valuable for calls for assistance by an officer. Closest units can be assigned as in other calls for service and directed with greater accuracy to the needed location, particularly in those cases where the original action was officer-initiated.

The "officer needs assistance" feature of some AVL systems is more properly a feature of a mobile digital radio system. The AVL system can add current unit location data to such a message whether it is initiated in the unit or away from the vehicle if the officer is equipped with an emergency transmitter and the vehicle is equipped with a corresponding receiver. The utility of this feature is very dependent upon the accuracy of location, as the other units responding should be able to locate the calling unit rapidly. Some techniques proposed utilize the calling unit's emergency visual and audible equipment to act as a beacon to other units. The lights and siren would be activated by the emergency transmitter carried by the officer when away from the unit. The utility of this feature is difficult to assess and it might even detract from officer safety.

2.1.4 Administrative Control

A great deal of data can be developed by an AVL system. The data, describing the calls for service by time and location coupled with the response, travel, arrival, and clearing times can be stored in various formats for administrative use. Other data such as beat coverages, patrol routes, and officer activities can be made available for analysis.

The value of data depends to a large extent on what is saved and what use is made of it. The value of AVL system data depends on the flexibility in data collecting and processing. Those techniques or systems providing timely location data on the entire fleet will provide more useful administrative data than those systems which locate only a few vehicles at any time, i.e., locate on demand. On the other hand, administrative monitoring can be performed on a sampling basis, for example, during two or three short periods per day; continuous 24-hour monitoring is not required for any administrative function.

The principal negative aspect of AVL is the continual surveillance of the units, i.e., the "electronic sergeant" aspect, which might be strongly resented by some officers, although the officer safety feature is a rebuttal to this concern.

The administrative data developed from an AVL system should provide a means of judging the effectiveness of various patrolling strategies and beat assignments or arrangements. The AVL system also provides a public relations function, in that the data can be used to accurately document activities in case of complaint or as an example of an effective means of maintaining discipline and administrative control.

2.1.5 Patrol Effectiveness

The availability of location data for development of patrol strategy is a major reason for use of an AVL system. The real-time dynamic reallocation of patrol forces can be established and verified with the location system. The long time effectiveness of patrol strategies can be determined from the administrative records.

The utility of AVL data for judging patrol effectiveness is very quickly diminished if the location accuracy is poor. It would be difficult to justify this application to support procurement of an AVL system if the accuracy were insufficient to tell which block or street was patrolled. This would be particularly true in cases where the record of unit location at some time was important for other reasons such as a citizen complaint. Entire fleet location reporting is preferred for this use.

2.1.6 Tracking, Surveillance, and Covert Uses

Keeping track of the location of containerized freight has been mentioned as a possible application of AVL. Actual requirements as to accuracy and coverage area have not been developed. If a practical technique can be developed which requires no intervention other than the placement of some device in or on the freight container, covert uses become feasible.

The technology is at hand for placement of a low-cost long-life, unobtrusive device on an unaware host, but no proposed AVL system has advertised this covert surveillance feature.

2.1.7 Other Applications

Sharing an AVL system with other users can result in negligible to substantial impacts on operational use. Those techniques which require an exclusive radio link for location and interrogation purposes* usually require a high speed data collection and computing facility at a centralized location. All users of these systems must be included in the polling cycle; the location data must be furnished to each user through a real-time information link. Conversely those techniques

*Examples are wide-band FM ranging and pulse time-of-arrival systems. Both are described in Section 2.2.

which can use the normal radio channels available to each user and require only a table look-up computation can operate virtually independently.

Other users of AVL range from non-law enforcement emergency service vehicles to transport and commercial vehicles. Fire and ambulance services operate in virtually the same manner in the urban environment and AVL would provide mainly administrative and public relations data on travel, response, and arrival times. Incidental data such as route used or return times might also be derived. Natural disasters or other large scale emergencies where many units are deployed would benefit from AVL. For example, fire units could be located and deployed efficiently during brush and forest fires that threaten suburban areas. Similarly, ambulances could be efficiently scheduled and routed to hospitals in multiple casualty occurrences.

Rural and highway law enforcement agencies pose a particularly difficult problem for most AVL systems. Neglecting the economic problem, the technical problem of providing reasonably accurate location data over a very large area is comparable with that of navigation systems except that the vehicle operator knows his location to greater accuracy than the ship navigator because of terrain and landmarks. Operational procedures and voice reporting of position information in these forces provide all the data required except that which may be desired for administrative purposes.

Public utilities might have an AVL requirement for keeping track of the emergency and service vehicles. This requirement is primarily administrative. Tactical deployment and dispatching in cases of natural disasters or unusual occurrences would be another consideration for use of AVL by such agencies.

Urban buses have been considered as a primary user for AVL systems and several systems have been implemented and tested. These systems use fixed-route techniques in which AVL data are used to control headway and scheduling on a real-time basis. The primary justification is better service, but there is a substantial economic benefit in the reduced number of field supervisors.

Taxis, urban freight delivery, parcel service, and dial-a-ride systems all are quite similar in operations to law enforcement in that a call for service requires a dispatch from a random location. Dispatching, scheduling, and administrative control functions would be facilitated with timely and accurate location information. The accuracy and timeliness requirements of the location data for these services have not been determined. It is likely that none of these users can justify installation of AVL for their sole use, but all would probably use AVL if it were available as a public utility or shared leased service.

2.2 Characteristics of AVL Systems

As mentioned briefly above, there are three basic types of AVL systems: dead reckoning, proximity, and radiolocation. Under each of these broad classifications there are a number of variations. Many different variations have been identified but considerably fewer have been seriously considered or demonstrated.

2.2.1 Dead-Reckoning Techniques

This type of AVL system locates the vehicle by measuring its direction and distance traveled from a known starting point. A radio link from the vehicle is necessary to transmit the location data. Direction and distance sensors are carried on each vehicle and data processing, either in the vehicle or at a central data processing site, is necessary to continually compute vehicle position. In either case, the radio link from each vehicle to the central data processing site carries location information in digital form. When a number of vehicles share a radio channel for transmission of this data, serious congestion can exist and some controlled sequencing of transmissions is required.

The accurate measurement of vehicle direction and distance traveled is difficult to make. The sensors usually consist of a compass to measure direction and an odometer to measure distance. Small variations in the earth's magnetic field are caused by metal structures, and odometer errors can be caused by changes in tire pressure and wheel slip. Since the determination of a vehicle's location depends on all measurements made since its starting point, errors accumulate, and after only a few miles a sizeable error can exist.

There are ways to reduce the errors of dead-reckoning The dispatcher can reinitialize the position of a vehicle based on verbal information from the officer; the officer likewise can reset the system when he is at one of a number of known positions. Automatic initialization could be accomplished by use of a network of proximity devices such as are described in the next section. When a vehicle is near one of these proximity devices, that known location is sent to the central computer to correct or reinitialize its position. If the data processing system includes a street map of the city stored in computer memory, a technique of "map matching" may be used to correct location errors. It is assumed that a vehicle is confined to a driveable surface or street in the city; if the indicated position is not on a street, the location is corrected to cause the vehicle to appear on the nearest appropriate street.

An example of how a dead-reckoning system determines a vehicle's present position is shown in Figure 1. Figure 2 shows the elements of a typical dead-reckoning AVL system.

2.2.2 Proximity Techniques

The proximity technique of vehicle location utilizes "signposts" in known locations distributed throughout the city. When a vehicle passes near a signpost, that fact is sensed and a unique identification of that vehicle and signpost is sent to a central location. The basic technique is illustrated in Figures 3 and 4.

The instrument at the signpost location is usually a continuously radiating device sending out a uniquely coded message. The vehicle is equipped with a suitable receptor to receive and store the message for subsequent retransmission to the base station and in this way inform the base as to the last signpost location passed.

Most techniques use a short range radio link from signpost to vehicle. The links range from low frequencies (190 KHz) to X-band (10 GHz). Of a number of proximity systems currently being proposed, one uses a frequency in the Citizens Band at 27 MHz and another uses a frequency at X-band of about 10.5 GHz. Elevated locations for the signposts are usually selected to achieve larger coverage areas, freedom from blocking by large vehicles, and lessened probability of vandalism. Signposts may not require FCC license if their power is low enough.

Accuracies of proximity systems are a function of the radius of influence of each signpost and density of signpost locations. Signpost density can be such that every road segment or intersection is covered, or there can be gaps in coverage. This system is especially amenable to accuracy tailoring and coverage area growth. However, increasing the spacing between signposts does not result in a simple direct lessening of accuracy, since the probability of avoiding the signposts increases significantly when there are large voids in the coverage. An approach that eliminates part of the problem where lesser accuracy is acceptable is the use of an "electronic fence" around an area so vehicles entering or leaving can be monitored. This will be described later.

Another way to improve location accuracy with increased spacing between signposts is to use a vehicle odometer to measure and transmit to the base station the distance traveled since passing the last signpost. Since direction of travel is not known, the direction must be inferred from previous signpost approaches and there can be an ambiguity if the vehicle turns.

Instead of radio emitters, buried permanent magnets can be used to provide a means of passive proximity location identification. In this concept, rows of permanent magnets are

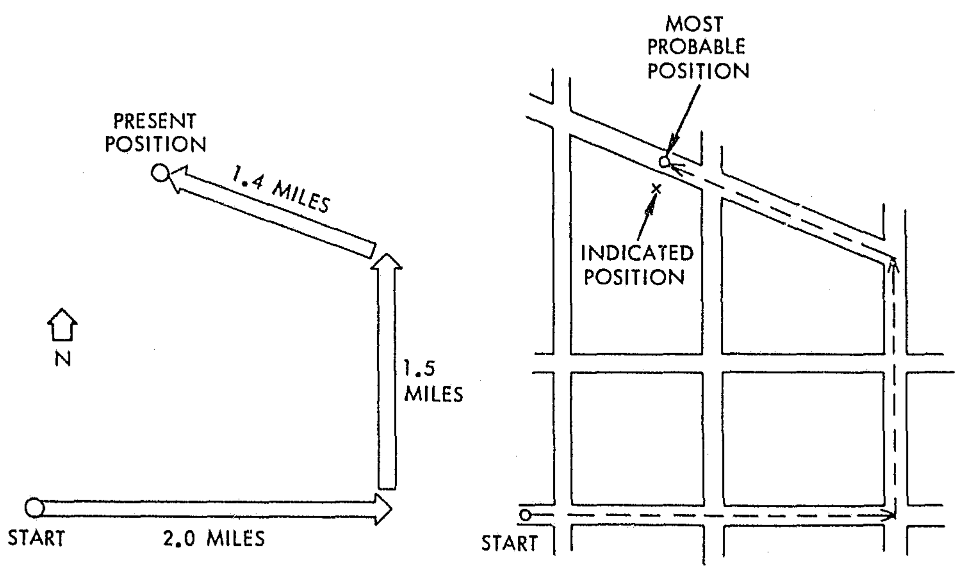

Fig. 1. Dead-reckoning AVL system. This diagram illustrates how, after starting at a location known to the computer, the present position of a vehicle can be determined from the distance traveled and direction of travel. With a computer-aided map-matching technique, the vehicle's location can be corrected to lie on a path consistent with the streets of the city.

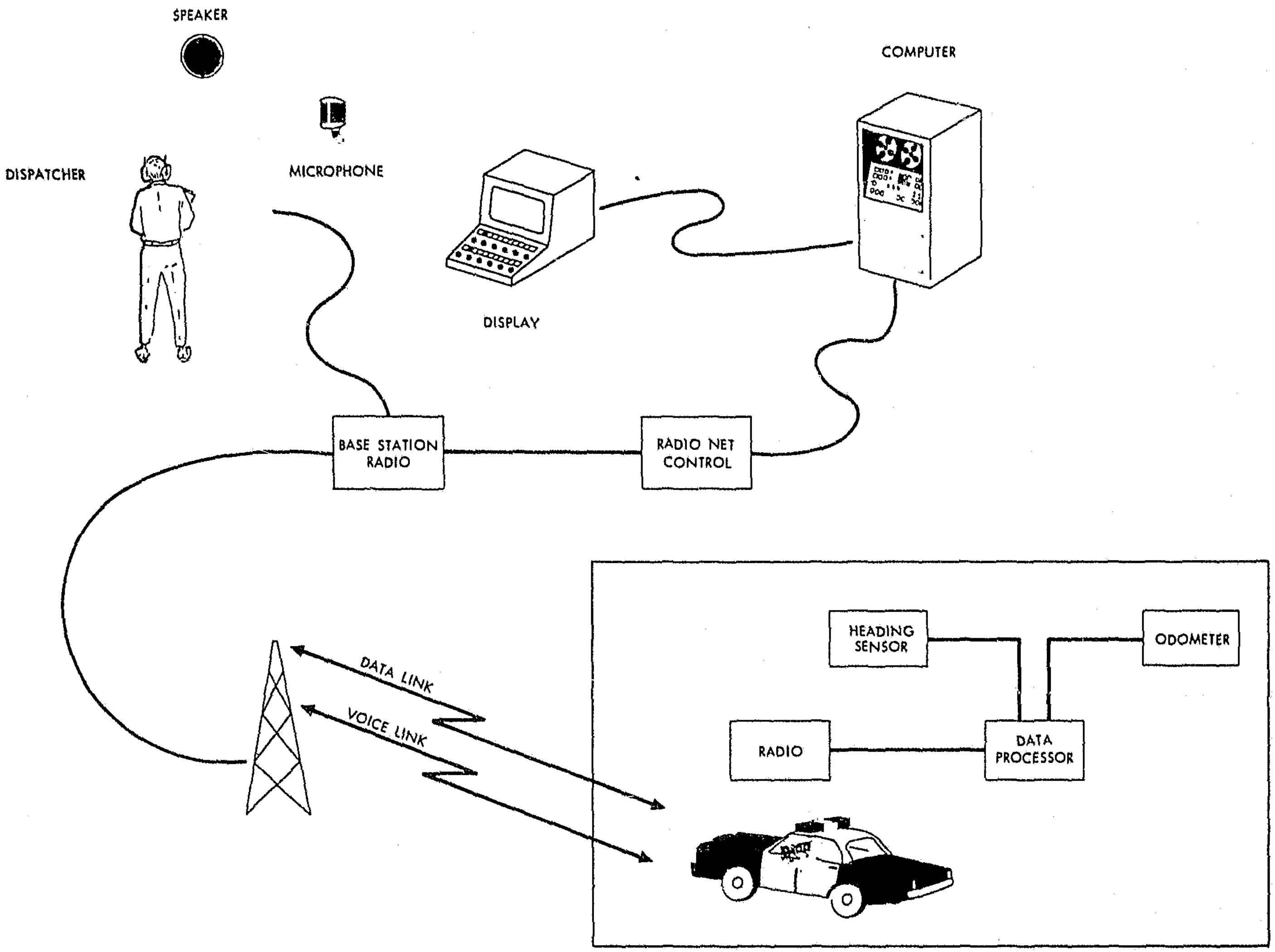

Fig. 2. Typical elements of a dead-reckoning vehicle location system

installed along vehicle lanes to provide a means of inducing a voltage in a sensing coil mounted on the vehicle. The magnets are placed in the pavement surface with either N or S poles pointed up to provide binary identification of the location. The sense coil in a moving vehicle detects signals of different polarities depending on pole orientation.

Ultrasonic and light radiations are possible practical approaches to avoid RF congestion and interference with other services. The ultrasonic waves are similar in length to X-band RF; consequently, horn or parabolic antennas can be used for focusing sound to a desired coverage area. The flashing light approach, either visible or infrared, is practical for short ranges. Both techniques are somewhat hindered by weather conditions, particularly fog, rain, and blowing dust.

Reflective patterns painted on the road or buried magnetic loops similar to those used for traffic signal control can be used. The buried antenna approach using traffic presence sensor loops was tested recently in San Francisco and New York for toll authority billing for buses. Antennas (buried loop) interrogate continually and receive responses from instrumented buses. The use of sensor loops as antennas is practical and has an added advantage in that weather-proof enclosures and power are available in the traffic signal controller.

As with the dead-reckoning AVL technique, a data channel using a radio link from each vehicle to the base station is required to relay the signpost code and vehicle identification. When a large number of vehicles share a radio channel for transmission of this data, serious congestion can exist. Some form of radio network control is needed.

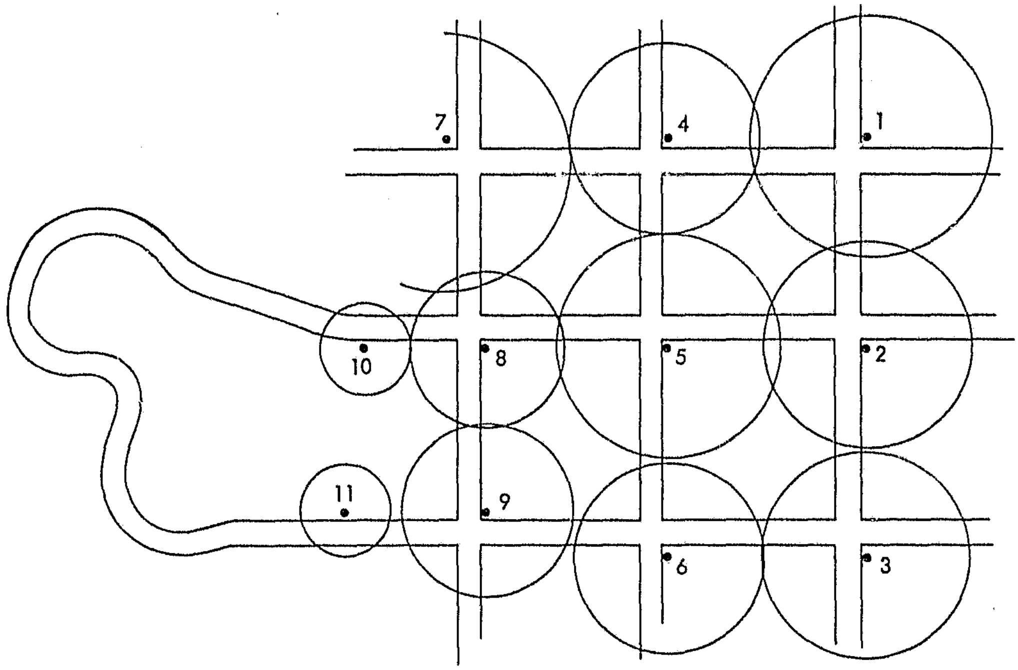

Fig. 3. Proximity AVL system. This diagram illustrates a proximity system using low power radio transmitters, each emitting a unique code, located at street intersections. The coverage of each transmitter is adjusted to provide minimum overlap with adjacent transmitters. Note that transmitters 10 and 11 are used to cover a remote mountain or rural road. If a vehicle had passed transmitters 8 and 10 in that order, but not transmitter 11, the vehicle would be located somewhere on the road between 10 and 11.

An important feature of a proximity system is that it can serve a large number of different users. Each user group must supply a data channel, but costs of initial installation and maintenance are shared.

The "electronic fence" is a variation of the signpost proximity technique. The fence is a narrow beam of RF or light or a buried antenna that detects vehicle crossings. The fences are arranged to enclose zones. This variation might be used in a rural area where entrances and exits of a zone are relatively few but where the area is large. Since the costs of a signpost system for complete coverage of a large area are high, it may be sufficient to know that a vehicle is within a zone, but not know its exact position within the zone.

Inverse proximity is another variation of the signpost technique. The signposts are equipped with receivers and the vehicles are equipped with either low power coded RF transmitters or ultrasonic, light, or magnetic devices. When a vehicle nears a receiver, the vehicle's code is received and relayed to the base station. Telephone lines may be used for this purpose, possibly in conjunction with existing call and alarm boxes. Thus, an RF data channel from the vehicle to the base station is not required for the inverse proximity technique.

The inverse proximity technique does not have the ability to handle large groups of users as do the other types of proximity techniques unless the telephone lines connecting the receivers are distributed to all groups of users. When two or more vehicles approach the same receiver, their signals will interfere and only one is likely to be detected.

The active electronic signpost requires a primary power source, which may cause difficulties in general applications. Since reliance is placed on either street lighting circuits or traffic signals for primary power, alternate sources will be necessary. Options other than utility power are radioisotope sources, solar cells, and long life batteries. Radioisotope sources are expensive and probably environmentally unacceptable. Solar cells coupled with a rechargeable battery could provide sufficient power, but will not operate properly in heavy overcast, snow-laden, or dust environments. Long life batteries are probably best, particularly if an interrogation mode of signpost operation is used. In this mode each vehicle is equipped with an interrogation transmitter and the signpost responds (uses battery power) only when an equipped vehicle is near. Some technique would be required to prevent a stopped vehicle from exhausting the reserve power of a nearby signpost (further interrogations could be inhibited when the same message had been received several times).

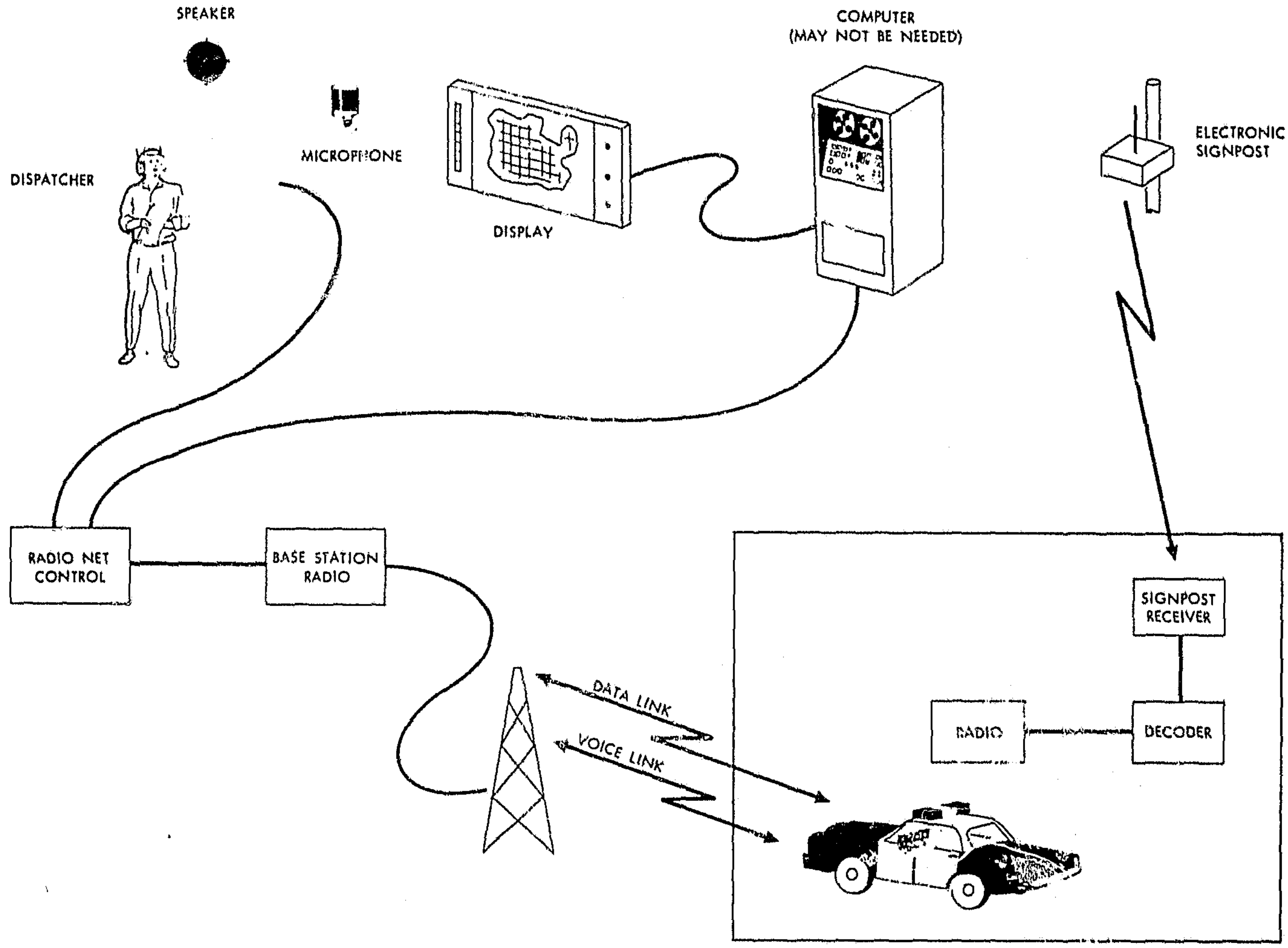

Fig. 4. Typical elements of a proximity AVL system

2.2.3 Radiolocation Techniques

Radiolocation techniques have been used for years for the navigation of ships and airplanes. Trilateration methods using three fixed sites determine a vehicle's distance from each of the sites by measuring the radio signal travel time. The knowledge of distance of the vehicle from each site determines the location of the vehicle. This type of system is called a range-range system and is illustrated in Figure 5. In order to measure the radio signal travel time, very accurate clock synchronization between the vehicle and the fixed stations is needed since both the time of signal transmission and signal reception must be known. Radio waves require slightly more than 5 microseconds (0.000005 seconds) to travel one mile, thus the synchronization must be to within a fraction of 5 microseconds in order to measure vehicle location to a fraction of a mile.

A version of a radiolocation technique that does not require time synchronization between the vehicle and fixed stations is called a hyperbolic system. In this system, the difference in radio signal travel time for signals traveling over two different paths (from/to each of two stations to/from the vehicle) is measured. The time difference corresponds to a distance difference for each pair of stations. A path of constant difference in distance from two fixed points traces out a curve which is called a hyperbola, hence, the name of this system. The vehicle must lie somewhere on this path. Using a third fixed site, another time difference and corresponding distance difference is determined. This gives another hyperbolic path, and the intersection of these two hyperbolic paths corresponds to the actual vehicle location. Figures 6 and 7 illustrate this technique. Hyperbolic systems require clock synchronization, but only among the fixed stations. This is much less costly than maintaining synchronization with

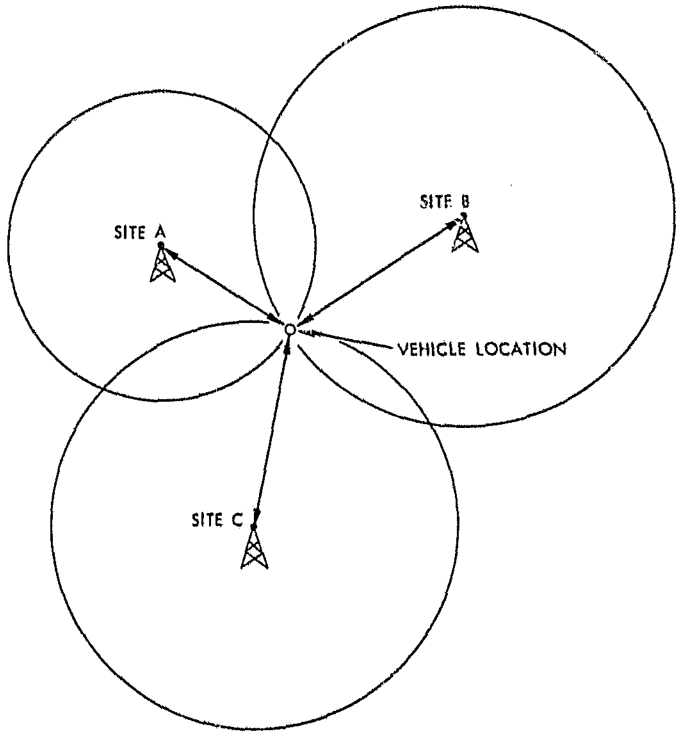

Fig. 5. Range-range AVL system. Three fixed sites measure the distance to a vehicle. The intersection of three circles of equal distance around each site determines the vehicle location.

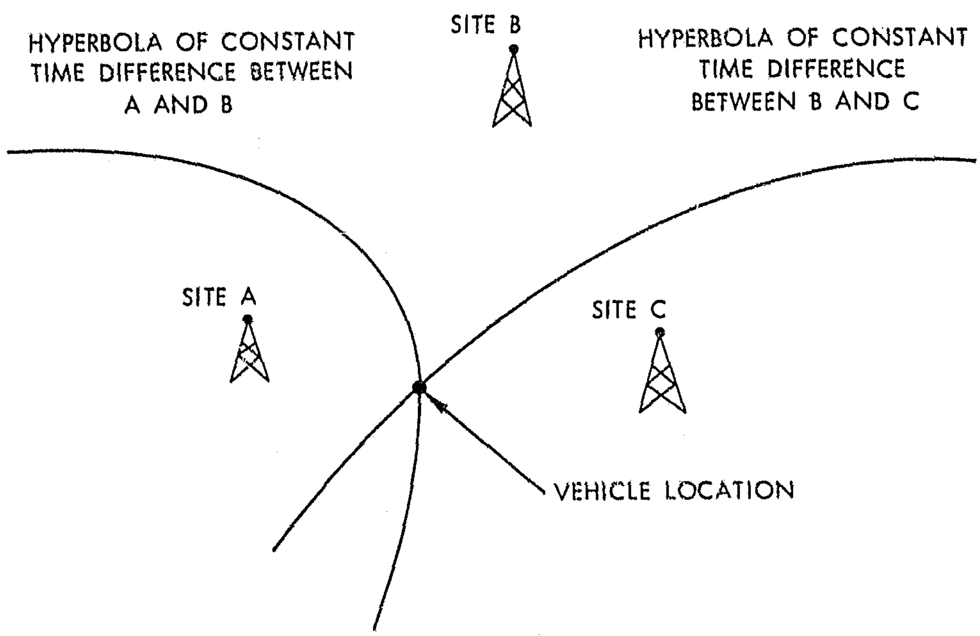

Fig. 6. Hyperbolic AVL system. Three fixed sites use the measured difference in radio signal travel time to determine the intersection of two hyperbolic curves.

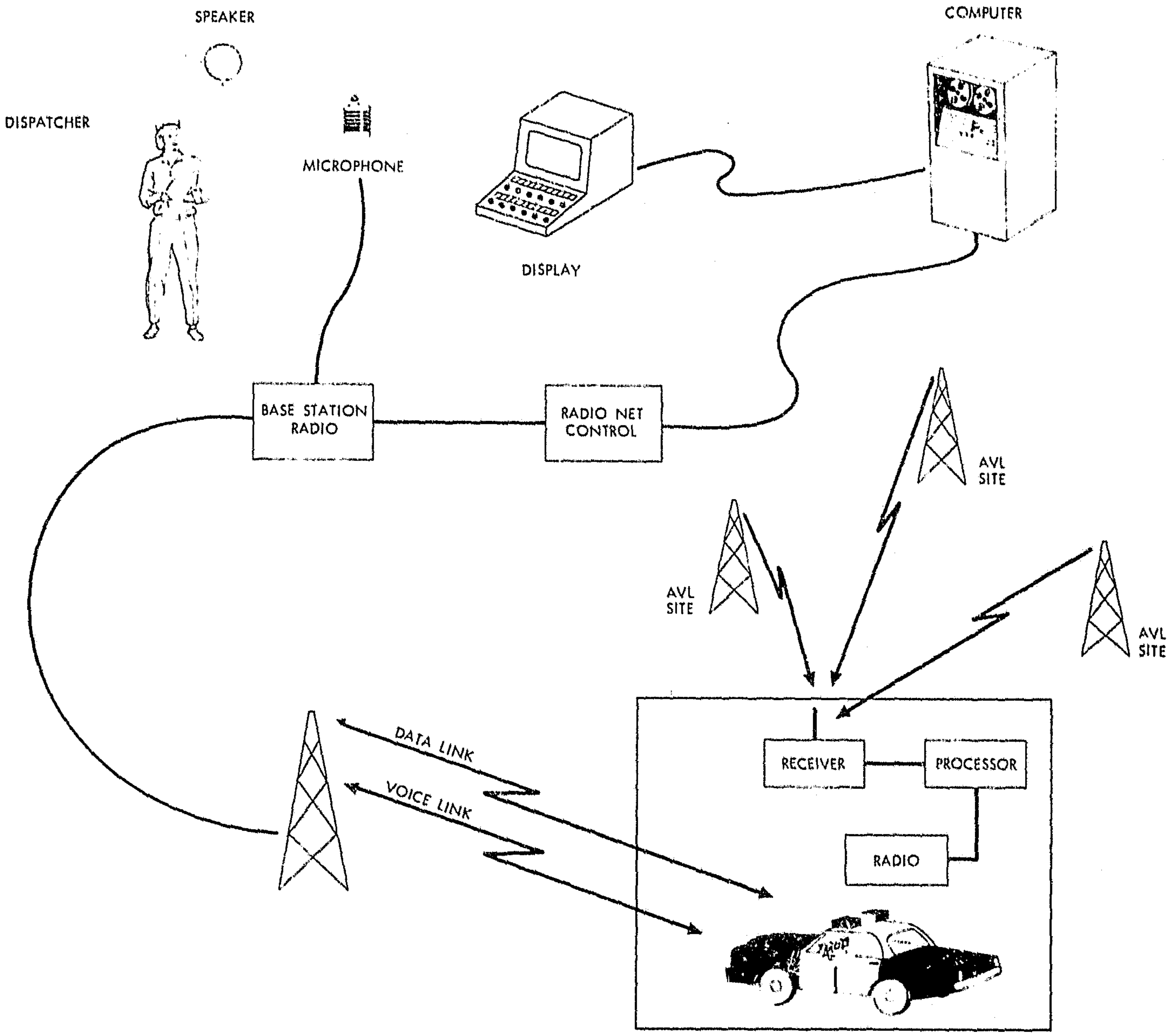

Fig. 7. Typical elements of a radiolocation AVL system

a large number of vehicles as is necessary with the range-range system.

Radiolocation techniques require radio transmission between the vehicle and a minimum of three fixed sites. The fixed sites may contain either the transmitter or the receiver. If the fixed sites contain the transmitters, then the vehicle must contain, in addition to a receiver, data handling equipment and a means (radio channel) for transmitting received information back to the data processing site for location computation and display presentation. Conversely, if the vehicles contain the transmitter, the fixed sites' receiver signals contain location information and it is sufficient to connect all receiving sites to a central data processing site for location computation.

In practice, more than three fixed sites are usually required to provide adequate RF signal level over the region covered, to reduce location errors by providing independent solutions to the location calculation, and to provide increased reliability for equipment failure.

In trilateration systems, either a pulse or a sine wave form of modulation is used. In the pulse modulation technique, a short RF pulse is transmitted. The receiving sites measure the time of arrival of the leading edge of the received pulse and establish the range differences. One system of this type which has been tested uses a fixed transmitting site emitting a short RF pulse. Each vehicle is equipped with a transponder which retransmits a short RF pulse at a known time after it receives a pulse. Pairs of fixed receiving sites determine the difference in arrival time of each vehicle's transmitted pulse and send this data to a central computing facility where each vehicle's location is determined using the hyperbolic method described previously.

In the sine wave modulation technique, the receiving sites measure the phase of the received modulation. The phase measurements determine the range differences. Low modulating frequencies are used so that phase difference repetitions do not cause ambiguities in the surveillance area. The tested methods used 2.7 KHz and approximately 18 KHz (phase patterns repeat at 111 km and 16 km, respectively). These systems have been termed narrow and wide band, respectively, since the first can be accommodated in a narrow band FM voice channel (25 KHz) while the second requires four adjacent channels (100 KHz). In comparison, the pulse method utilizes up to 10 MHz of bandwidth to preserve the leading edge of the pulse.

All of the foregoing trilateration schemes suffer from the very phenomena that makes VHF voice transmission in dense areas possible – multipath, which tends to extend, smear, distort, or eliminate the direct-line-of-sight signal from the transmitter to the receiver.

There are three principal wide area navigation schemes, used primarily by ships and airplanes, which use hyperbolic techniques: Omega, Loran, and Decca.

Omega is a very low frequency (10-14 KHz) time-multiplexed technique. The relative phase of signals on the same frequency transmitted in sequence from several sites defines a set of "lines of position". The intersections of the "lines of position" determine the receive location. There are ambiguities in position since the phase patterns repeat every 15 km or so. Other frequencies transmitted in a 10-second sequence from each transmitter provide information to resolve these ambiguities, but these would not be required in most AVL applications. Signal phase information must be stored in the vehicle for comparison with subsequent transmissions. This storage is on the order of 1 to 4 seconds but could be as large as 8 seconds. A moving vehicle could travel a substantial distance in this interval. Differential Omega is merely a technique for reducing the effects of local propagation anomalies. A fixed receiver at a precisely known location is used to remove these anomalies over a 15 to 30 km radius through continuous monitoring of the received signals.

Loran is a combined pulse and phase time-multiplexed scheme for determining "lines of position". Pulsed signals from three or more stations are transmitted 10 to 33 times a second in coded groups. The receiver measures the time-of-arrival difference from given pairs of signals to determine the "lines of position". No ambiguity exists and each "line of position" is unique geographically. Differential Loran also uses fixed site receivers to remove local propagation anomalies. Relay Loran retransmits the received signals to a base station for time differencing.

The Decca system operating in the 70-130 KHz region is a continuous wave phase difference technique with each transmitter operating on a different frequency that is harmonically related to those of the other transmitters. The location is determined by simultaneous reception and comparison of the phase of the signals. The "lines of position" determined by the phase measurements are not unique and special signals are transmitted frequently to enable the determination of the correct one.

A disadvantage of the wide area navigation schemes for AVL use is the high unit cost of the receivers and consequently the high system cost, since each vehicle must be equipped with a receiver.

2.2.4 Combined Techniques

It may be desirable to combine features of two techniques for some AVL applications. For example, the dead-reckoning technique requires the initial position to be accurately known. A limited proximity signpost system would provide a number of calibration points throughout the coverage area for this purpose. Another example is the use of a proximity technique in a downtown high rise area and a radio trilateration technique in the suburban or rural area.

2.2.5 Other Considerations

Many important AVL system elements are often not discussed in systems descriptions. These include:

(1) The data channel from vehicle to base station.

(2) Data collection requirements.

(3) Computation requirements.

(4) Display requirements.

(5) Interfaces to other subsystems.

(6) The integration of the system into the dispatch operations.

Data Channel

In some systems, the vehicle-to-base data channel carries location information developed within the vehicle. Normally, the information can be transmitted by digital means over a single voice radio channel, but two problems must be solved. First, any delay in sending vehicle location information to the base station will result in location errors due to vehicle motion. At 30 mph, a vehicle will move 134 meters (440 feet) in 10 seconds. Second, a large number of vehicles will want to share a radio channel for communicating the location information. Radio network control methods must be introduced consisting of polling or contention operating modes.

Synchronous polling is a technique in which each vehicle reports the current location at a preassigned time within the polling sequence. The start of the polling sequence is determined by a signal from the base station which synchronizes a timing device in each vehicle. Each vehicle keeps track of the time elapsed since the start of the sequence and at the preassigned time turns on a transmitter and sends the location data.

This technique is relatively inflexible, requiring physical changes within the vehicle equipments to modify the sequence. The use of the RF channel is quite efficient, as communication is primarily one way and the various radio-turn-on-and-off transients can be made to overlap to improve the efficiency. Resynchronization by the base station depends on factors such as fleet size and stability of the vehicles' timekeeping equipment. With added equipment in the vehicle, changes required to alter the sequence can be made by signals from the base station. This additional equipment complexity is equivalent to that required for commanded polling.

In the commanded polling technique a transmission from the base station is required for each location query. Usually the vehicle identity code is transmitted and when it has been received and recognized the addressed vehicle responds with its location data. A substantial amount of RF channel time is utilized in radio-turn-on-and-off transients, particularly if only a single frequency is available. These transients can quickly dominate the channel and restrict the number of vehicles which can report in a given time.

A useful variation of the command technique is one in which the base station transmits a signpost location code. Any vehicle which is near that signpost and has that code in its location register will respond. In this manner, the identities of vehicles near a particular location can be determined.

Volunteer polling, usually called contention, is one in which a vehicle transmits location data to the base station without a request. The conditions for transmitting require that the RF channel be clear. In a single frequency communication link, it is not always possible for every vehicle to "hear" every other vehicle; therefore, some transmissions may suffer interference. If two frequencies per channel are available, the base station can transmit a "busy" signal which informs the vehicles that the channel is occupied. Variable random delays in vehicle turn-on time after a channel has been vacated have been proposed to prevent some vehicles from dominating the channel.

Other conditions for transmitting location data require that a certain amount of time has elapsed since the last transmission, that a new signpost identity code has been received, that a minimum distance has been traveled, or a combination of these. A change in status might also be a reason to transmit location data.

As mentioned above, synchronous and commanded polling techniques can be combined so that the synchronous sequence can be modified without physical access to each vehicle. The synchronous technique can also be designed so that some vehicles respond several times during the entire sequence while lower-priority vehicles respond only once. Modifying the component sequences within the entire sequence by command yields a very flexible polling technique. Little can be done to modify a volunteer polling technique other than changing the conditions for reporting.

Data Collection

If the AVL system is to be used for purposes other than response time improvement (e.g., administrative and management purposes), collection of location data becomes an important consideration. The ultimate uses of the AVL system will determine the type of polling technique used, and will influence operational modes.

In the dead-reckoning techniques, a virtually continuous record is developed of the location of all of the vehicles in the fleet. Each new location determination is dependent upon the last, so continuous surveillance is required. In the inverse proximity systems, the identities of the vehicles passing monitored signposts are also collected at a central location.

Other location techniques which provide absolute location information can operate in a commanded or volunteer polling fashion, especially if response time improvement is the only consideration. Proximity systems which are primarily operated in the volunteer mode dependent on signpost passage will also provide a virtually continuous record of the fleet locations. If the proximity system is augmented with odometer or time-of-signpost-passage information to improve accuracy, then a more detailed history of vehicle locations can be obtained. Proximity systems operating in a command mode, either by vehicle or signpost identity, will supply information of current use to the dispatcher and for future response time analysis.

Computations

AVL. The computation required to convert the raw location data into directly usable or easily interpreted vehicular location expression is a function of the AVL technique employed. Proximity (either direct or inverse) systems have raw location data in the form of a signpost or equivalent identity code that is unique to the geographic location where it is installed. The computational problem is a straightforward table look-up which relates the identity code to the location.

The location may be expressed as an intersection of two streets or a block location on a street indicating a street segment between two streets or a numeric and a street indicating the range of property addresses in the domain of the signpost. Other information that can be included, such as beat number, crime reporting district, census district, map coordinates, etc., depends on the use to be made of the location data. The map coordinates are necessary if estimates are to be made of the response time for the call for service.

The raw location data may be augmented by odometer data from the vehicle or local vehicle time of passage near the signpost. This data, together with a past history of the track of the vehicle, can be included in a predictor-corrector algorithm to estimate the current or future location of the vehicle. New data estimates may be necessary if the time of last passage is not current.

Computations are more complex for radiolocation systems using hyperbolic coordinates from either established navigation systems or local time (phase) of arrival systems. Two techniques can be used: an analytic solution from signal arrival time differences from three or more sites, or a weighted least-squares estimation based on arrival times or differences. In either case, the result of the computation is a location of the vehicle in geographical terms such as latitude and longitude, northings and eastings, or X and Y. These data may also be amended with other information for statistical and reporting purposes.

Dead-reckoning systems transmit raw data from the vehicle either as distance and heading changes or changes in north and east directional distances — the latter if resolution of distance by direction is done onboard the vehicle by a small preprocessor. In either instance the computed location information is geographical in nature.

Display. The location data developed for proximity systems, being primarily in street terms, is suited for direct tabular or listed output. If used for map or overlay displays, the signpost location or extrapolated vehicle positions must be converted to geographical equivalents.

Those techniques whose computations yield geographical information are directly usable with map displays. The difficulty with these techniques lies in relating the geographical data to street(s) locations. It is difficult to program a routine which would indicate correctly which of four streets a vehicle is using when the AVL system locates it in the center of the block. For this reason, tabular displays would be difficult to interpret directly and quickly.

A technique often used in dead reckoning corrects the raw data vehicle position by means of a computer-stored map, assuming that the vehicle is always on a dedicated street. Each departure from such an assumption is corrected by moving the computed location of the vehicle to the nearest street and using that location as the basis for the next computation. This technique is applicable to other AVL systems if the inherent accuracy warrants, and allows for street name formats in tabular displays.

Data Base. The street name or map type data developed from the raw location data, together with time and vehicle identity, forms a historical track of the position of each vehicle. The accuracy of this track depends on the inherent accuracy of the technique together with the interval or speed of polling. Amending the location data with other data of an identity and statistical nature can lead to a data base which can be very useful, especially for patrol and crime prevention analyses. The historical record of location is rather meaningless without the related record of status changes or dispatches, inquiries, and administrative actions.

Displays

The display of vehicle locations derived from the AVL systems can be accomplished with several degrees of complexity, ranging from printed listings to cathode ray tube tabular and graphical presentations to large wall map displays. To a large extent, the type of display is related to the function and responsibility of the user.

Tabular. In a medium or large size city a printed or cathode ray tube (CRT) display of the current location of each vehicle would have little use except as a historical record. This is particularly true in continuous surveillance polling schemes since the amount of data developed would be very large. If a small number of vehicles are deployed or the display limited to those vehicles controlled by a single dispatcher, a

CRT display augmented by the vehicle status constitutes a minimum AVL display in terms of cost and complexity.

Ordered Table. This is a modification of the CRT tabular display of location and status. It requires a dispatcher input of the location of the call for service. The list of vehicles is then listed by minimum response time as a function of both availability and current location.

Map Overlay. In this display the physical position of each vehicle in a particular geographic area is superimposed on a map of the area. This type of display can be accomplished by several methods: electronically, mechanically, optically, or with software. All of these are relatively complex.

A computer-stored map can be used to display the geographic area of interest. The vehicles in the area are displayed together with status and identity on the CRT map. The amount of detail to be shown can be dependent on the amount of area displayed. Both zoom (continuously variable area magnification) and map centering can be accommodated, but the software to handle all of the various niceties can become prohibitive in cost and complexity.

Another technique uses a video camera to develop the map portion of the display, either from a repertoire of small maps on slides or a large map. The latter technique requires that the video camera be under control of the dispatcher or watch commander. Multiple dispatcher stations would be difficult to accommodate with a single camera. Another difficulty in this technique is the matching of magnifications and positioning of the displayed map and vehicle locations.

Optical mixing either by projection or super-positioning methods can also be used. A gas plasma display with rear projection of up to 256 separate slides has been demonstrated. This type of display probably would not have zoom or variable centering.

Wall Displays. Wall displays can range from simple gross detail maps with lights or numeric displays at principal intersections or beat areas, to fine detail maps with projected moving display superimposed. The wall map in general is a wide area display covering the entire jurisdiction. It usually cannot be changed in size or a particular area of interest emphasized. The principal justifications for this type of display are public relations and administrative. The wall display has strategic and tactical worth in cases of widespread natural disasters, civil strife, or other unusual occurrences.

Interfaces

Mobile Terminals. Vehicular hard copy or other alphanumeric display devices invariably require a digital communication link. In most instances, the terminals are equipped with keyboards for messages initiated from the vehicle. Those AVL techniques which are compatible with volunteer polling can use the established digital link used by the terminals. The interface between the two subsystems, the AVL and the mobile terminal, is a link between the message register and the location data register. Such a link would allow adding location data to any message from the vehicle. The decision as to whether the message would be added or not is dependent on manual control, elapsed time since the last message, or the type of message.

In addition to the capability of originating AVL messages, the mobile terminal system is usually equipped with a selective calling or similar technique which is nearly equivalent to the polling required for some AVL systems. The message from the base station can be a request for location data from the AVL subsystem, which can then respond without manual intervention.

Status. Status keyboards are similar to mobile digital terminals except for the greater restrictions on message types. These restrictions should not inhibit joining the AVL subsystem to the status reporting system in the same manner as the mobile terminals.

Computer-Aided Dispatch. The interface between an AVL and computer-aided dispatch (CAD) system is almost wholly within the base station computer complex. If a single computer is being used for AVL and CAD functions, the interface is purely a programmatic or coding means of transferring information from one routine to another. On the other hand, if there are separate processors for each function, a real-time data transfer such as direct memory access is required to transfer location data to the CAD processor.

If the CAD system is used in a search mode, where the closest vehicle to a call for service is to be found, the CAD must interface with the polling subsystem of the AVL system.

Officer Emergency Alarm. The "officer needs help" emergency alarm may be associated with his vehicular voice radio, his vehicular mobile digital terminal, or his personal portable radio. If the alarm originates from the vehicle, its position is known either from previous information or from a current polling sequence. If the emergency alarm originates from a personal portable radio, it is not within the present AVL state-of-the-art to automatically locate that radio's position. The best alternative is to locate the vehicle assigned to the officer. If the officer is on foot patrol without a vehicle, an AVL system provides no real help in locating him.

Integration

In law enforcement use an AVL system is just another tool for the efficient management of police resources. Just as the mobile radio has been integrated into everyday use, AVL needs to be likewise integrated. It is important that the needs of the dispatcher be carefully considered in the design of a display device. Too much information or data which requires interpretation can increase the dispatchers' workload. The marriage between a CAD system and an AVL system is a natural one. The method by which the two interact and the resulting human interface should be given serious consideration in the design phase of either.

3. PLANNING GUIDELINES: ANALYSIS OF REQUIREMENTS

3.1 Accuracy Requirements

Requirements to be met by an AVL system must be based upon the purpose(s) of the system. In Section 2.1, seven applications of AVL were described. Accuracy requirements for each of these purposes are defined in the following paragraphs.

3.1.1 Dispatching

The purpose of this application of AVL in police dispatching is to reduce response time. This can be achieved if the closest car to an incident is dispatched, as opposed to always dispatching a beat car to any incident within a beat. Errors in vehicle location will result in some "wrong" dispatches where the closest car is not sent, but some other car which must travel farther and longer. Larson (Ref. 2) and Knickel (Ref. 3) have determined the average extra distance traveled by a car responding to an incident, when the closest car is not dispatched. Since, even with no AVL system, there is some chance of dispatching the closest car, the extra travel time, when averaged over all dispatches is reduced moderately. The results of Larson's study are shown in Figure 8 for a 9-sector command (each sector 1 mile square), an average response speed of 15 mph, and cars available when needed. This shows a rather modest reduction in average response time: 20 seconds for a perfect AVL system and 10 seconds for a 867 meter (2844 feet) AVL system. AVL system error specified here is for a 95 percent confidence level, that is, 95 percent of all location determinations will have an error no larger than the value given. Larson also shows that the average travel time to an incident in a sector by a car within that sector is 2.6 minutes, again assuming 1 mile square sectors and 15 mph average speed. Thus, AVL saves 10 - 20 seconds for a 6 - 12 percent reduction in average travel time. However, the accuracy requirements on the AVL system are not particularly demanding; a 10 percent reduction in average travel time corresponds to an AVL error of about 400 meters (1300 feet). As the number of sectors in the command is increased and as the utilization factor (percent of cars busy) is increased, additional savings in response time can be expected. A figure of 20 percent reduction in average travel time is about the most to be expected.

To realize the reduction in response time achievable with AVL, the traditional dispatching of beat or sector cars to an incident within that sector must be modified. Dispatching the closest car regardless of beat assignment is necessary, but results in a large percentage of vehicles being out of their assigned beat, depending on how busy the vehicles are handling calls. Larson has simulated a 9-sector dispatching process where the closest available car to an incident is dispatched. Figure 9 shows the results as the percentage of intersector assignments vs. the average utilization factor of all vehicles. Even for moderate utilization factors (0.30 to 0.40), 40 to 50 percent of assignments are "out-of-beat".

3.1.2 Tactical Control

The use of AVL in positioning units during hot pursuits, blocking escape routes, or deploying units during civil strife or natural disasters provides command capability without the

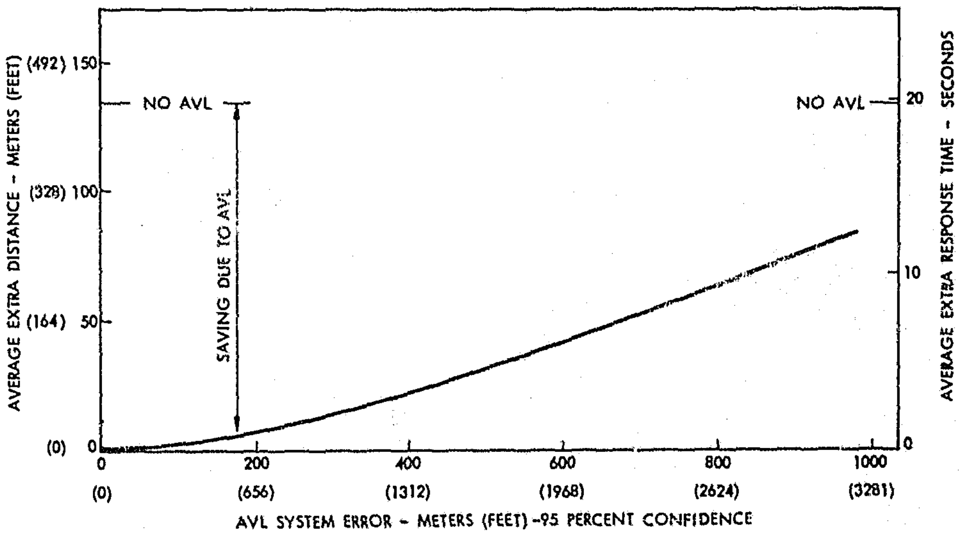

Fig. 8. Extra travel distance and extra travel time for non-perfect AVL system

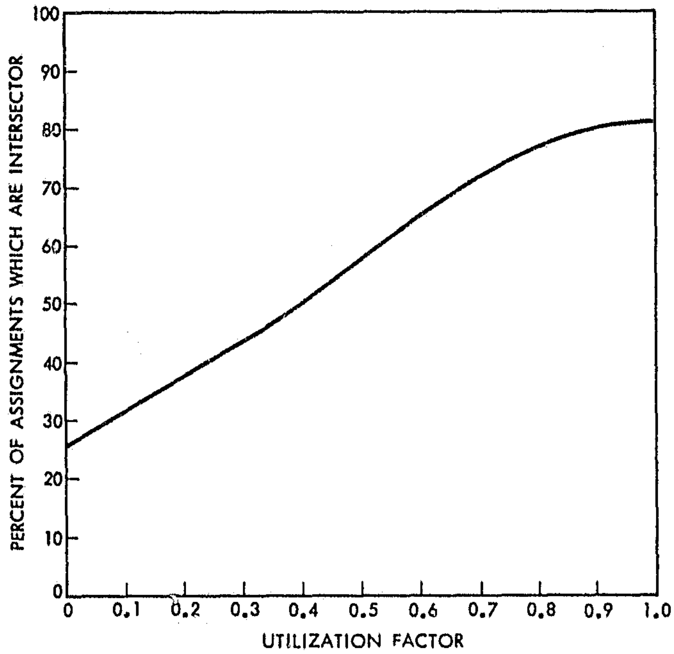

Fig. 9. Percentage of intersector assignments vs. utilization factor for closest car dispatching (Ref. 2)

need for voice reports of current position. Establishing an accuracy requirement is somewhat subjective, but it seems logical that knowledge of position of each unit to within one city block is adequate.

Defining accuracy requirements in terms of city blocks presents a problem because city blocks usually are neither square nor of standard size. Certain areas of New York City contain 240 blocks per square mile; the central area of Los Angeles contains 166 blocks per square mile. For the purpose of this section, we will use the central Los Angeles value, which gives an average block of 125 meters (410 feet) on a side. The reader can examine his own city characteristics to translate block size to linear accuracy requirements.

Assuming a city block of 125 meters (410 feet) gives an AVL system accuracy requirement of 125 meters with a 95 percent confidence level for tactical applications.

3.1.3 Officer Safety

When an officer in an unknown location requests assistance, or if an officer is missing, AVL may be used to locate his vehicle. In this case it may be prudent to require that the AVL system determine the location to within 1/2 city block or 62 meters (205 feet) with 95 percent confidence. With this accuracy a vehicle can be located quickly even in alleys or industrial area mazes.

3.1.4 Administrative Control

The use of AVL for this purpose can take many forms. Among these are reconstruction of past events, public relations, and supervisory functions. For the latter, an AVL system might be considered an "electronic sergeant." It is difficult to determine a specific accuracy requirement, but an error of several city blocks might be tolerable. Thus, the accuracy requirement might be stated as 250 meters (820 feet) with 95 percent confidence.

3.1.5 Patrol Effectiveness

AVL data can be used for analyzing the effectiveness of different patrol strategies. In a sense, this is similar to the administrative control application; thus, the accuracy requirement is similar (250 meters with 95 percent confidence).

3.1.6 Tracking, Surveillance, and Covert Uses

AVL accuracy requirements for this use can be severe. A requirement similar to that for officer safety is expected (62 meters).

3.1.7 Other Users

A wide variety of other users, ranging from bus fleets to freight delivery systems, may share an AVL system with a law enforcement agency. It is expected that accuracy requirements will be no more stringent than those of law enforcement.

3.2 System Accuracy Considerations

There are several technical performance parameters for AVL systems that affect both design and expected performance. The parameter which usually elicits the most interest is accuracy of location. A given technique will have a certain "ideal" accuracy for locating a vehicle, but this value is usually degraded when the technique is configured into a system.

The reduction in accuracy is due to several causes such as vehicle motion, delay in vehicle-to-base data transmission, processing time to relate vehicle data to a physical location, and delay in displaying the location on a map or other output device.

The amount of data which must be sent to or from the vehicle is a function not only of the location technique, but of the number of vehicles in the system, the area of the coverage, the density of streets or intersections in the area, and the shape of the area. The quantity of data, together with the polling technique and availability of RF channels, determines the delays in transmitting vehicle data, which in turn affect system accuracy.

The time required for the vehicle to receive or generate the data required for determination of its location is primarily technique dependent. For dead-reckoning, proximity, and radiolocation systems where location information in the vehicle must be transmitted, processed, and displayed, a significant dilution of the technique's basic accuracy is caused by vehicle motion; that is, the vehicle can travel a significant distance after its location is measured and the data displayed to a dispatcher. This effect has been investigated for a case where the speed of all vehicles in the fleet is distributed exponentially, i.e., a few are going fast but most are going slow, with one-half the fleet traveling at a speed of 15 mph or less. If we define the polling interval as the time between successive location transmissions from any one vehicle in a fleet, all of which are being polled sequentially, we can determine the error in location due to vehicle motion. Figure 10 illustrates the effect of polling interval on the inherent AVL measurement accuracy. For example, a long polling interval (10 seconds) degrades the accuracy of a good AVL technique (25 meters) to a system accuracy of 150 meters. This dramatically shows that the design of the communications channel must be considered as part of the total AVL system since it can have a large effect on the system accuracy.

Proximity AVL systems do not necessarily have overlapping regions of coverage. Generally, there are locations where the vehicle position is not sensed and the vehicle can be considered "lost" within some region of uncertainty. This is equivalent to location error. To investigate the relationship between location error and signpost spacing, we will use the concept of signpost density expressed in terms of signposts per square mile. It is assumed that the influence of each signpost extends over one intersection only. Signposts are not necessarily located at each intersection. Figure 11 illustrates a typical arrangement of proximity devices in a city street grid. The resulting AVL location error as a function of signpost density is shown in Figure 12 for the case of square city blocks with a density of 90 blocks per square mile. This figure is based on vehicles traveling in fixed direction for various distances between proximity devices.

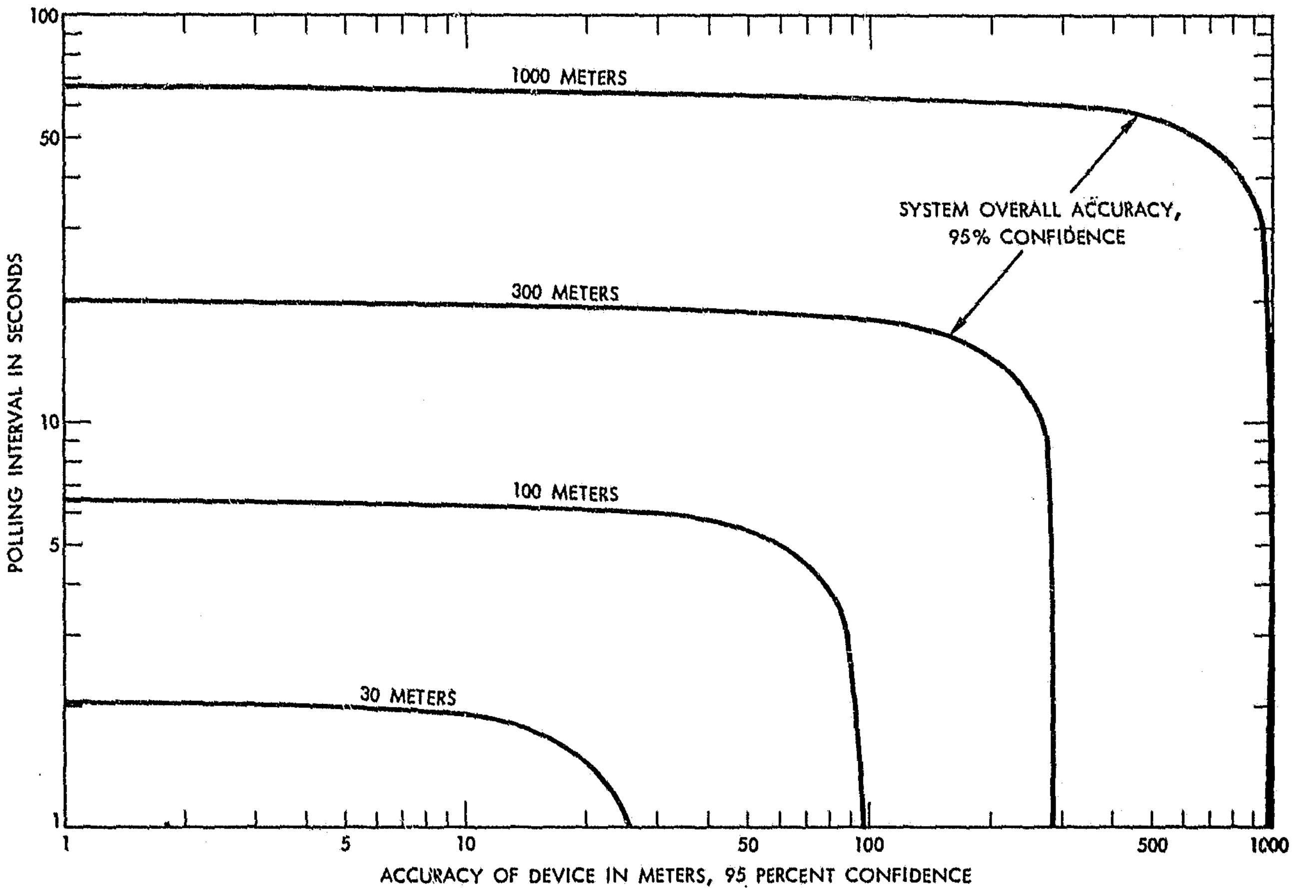

Fig. 10. AVL system accuracy

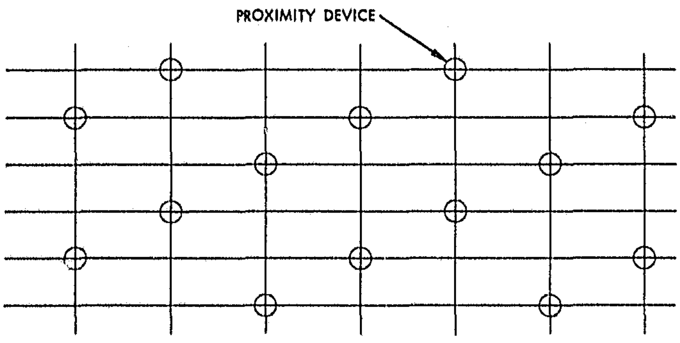

Fig. 11. Street intersections with proximity devices. Not all intersections are instrumented with devices. In this example the ratio of instrumented to total intersections is 1/3.

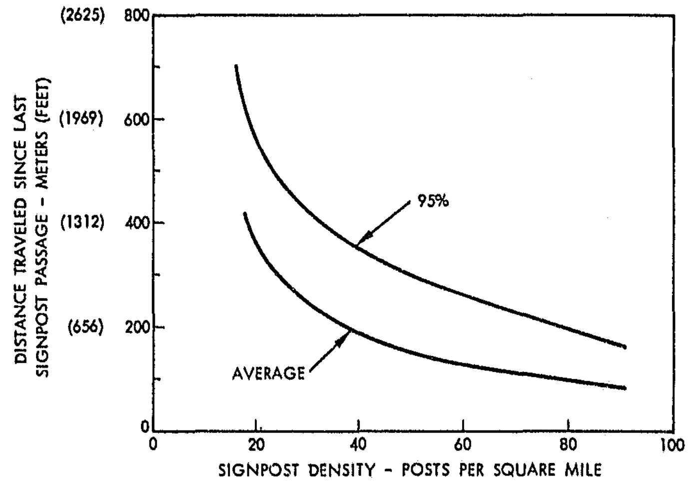

Fig. 12. Distance traveled since the previous signpost passage for a proximity system. This is equivalent to uncertainty in vehicle location which is location error. Square blocks and a density of 90 blocks per square mile were assumed for this case.

If a delay occurs in transmitting and processing the information that a vehicle is at an instrumented intersection, additional errors, as described in the previous paragraph, are incurred for cases when the vehicle is in motion.

Dead-reckoning systems determine vehicle position by accumulating direction and distance information from some starting point, as described in Chapter 2. Thus position error will also accumulate, although a map-matching technique can be used to reduce the errors. Even with map-matching techniques, a vehicle's computed position occasionally will be on an incorrect street and can be considered "lost." An important measure of performance for this type AVL system is the distance traveled or time elapsed, from position initialization to time of loss. Thus, in addition to a system accuracy specification in terms of distance from true position, a specification on the mean time between "losses" of a vehicle is important for systems where it is possible to "lose" a vehicle.

3.3 Other Requirements

Numerous other requirements must be considered, for example: frequency of information update, interface with the vehicle and communications equipment, interface with city services, display techniques, historical reports, equipment reliability, radio spectrum usage, training, and maintenance. These and other considerations are described in the next chapter.

4. PLANNING GUIDELINES: SYSTEM DESIGN CONCEPTS

4.1 Design Examples

As an aid to the planner considering implementation of an AVL system, several design examples with cost estimates are presented. First, a word of caution: the examples describe typical concepts only; many other concepts are feasible. Individual city physical characteristics, police department operating policies, and equipment developments make the cost estimates subject to wide variations. Nevertheless, the following examples should be of value to illustrate the design and cost considerations of the three selected AVL types in three model cities.

4.1.1 Model Cities

Three model city characteristics have been developed. Tabulation of these characteristics for a small, medium, and large city are given in Table 1.

4.1.2 AVL Techniques

Three AVL techniques are used as examples: a dead reckoning system using a vehicle odometer and compass, a proximity technique using RF signposts, and a radiolocation technique using a pulse time-of-arrival method.

The first two examples use techniques that produce location data in the vehicle; thus, a vehicle-to-base data link is required. Vehicle radios are included for such purposes. Data transmission is at 1500 bits per second, and simple parity coding is used for error detection. The mobile radio has a fast transfer time from receive to transmit mode. A value of 10 milliseconds is assumed, which is feasible with modern solid-state radios. A commanded polling scheme is used in which each vehicle responds with its current location message when addressed.

Vehicle locations are displayed to dispatching and supervisory personnel by cathode-ray-tube (CRT) devices, which give vehicle position on a city map grid. Map data is stored in a computer memory for this purpose. Although it was mentioned earlier that a technique of map matching could be used to improve the location accuracy of AVL systems, such a technique was used only in the dead-reckoning example.

Following a description of each of the three AVL system examples, characteristics are summarized in Table 2. Tables 3 - 5 (see Section 5.2) present cost estimates for these systems:

Table 1. Model City Parameters

	Small	Medium	Large
Population	30,000	300,000	3,000,000
Area, km^2 (miles^2)	10 (4)	100 (40)	1000 (400)
Dimensions, km	2.2 X 4.5	7.1 X 14.2	22.3 X 44.7
Number intersections*	350	3,500	35,000
Vehicles, patrol/total	5/10	50/100	500/1000

Assumptions:

(1) *Population.* The population of the model cities is based on population densities of 3000 per km^2 (8000 per mile^2).

(2) *Shape.* The assumption is made that the cities are rectangular with a 2:1 length to width ratio. The development of most cities either along a river, railway, or coastal harbor usually results in one dimension being significantly greater than the other. The choice of a rectangle is felt to be slightly more realisitic than the choice of a square or circular city.

(3) *Intersections.* The number of intersections in each city is based on street density measurements of randomly selected areas of actual cities. An average block aspect ratio of 2:1 is assumed, which means that the average block size is 122 m X 244 m (400 ft X 800 ft).

(4) *Vehicle Fleet Size.* Two classifications of vehicles are assumed for each city: patrol units, and all instrumented vehicles. An assumption is made that one-half the fleet is patrolling while the remainder is involved in investigative and administrative functions, or is out of service.

(5) *Building Distribution and Topography.* A low-rise building distribution is assumed for comparison purposes. The topography of the model cities is assumed to be essentially flat without "blind" radio areas or special areas that might adversely affect any particular technique.

*Based on 20/80 percent ratio of 64/28 blocks/km^2.

Dead Reckoning

A vehicle-mounted odometer pick-up, magnetic compass, and digital encoder are required to interface with a standard FM mobile radio. Each vehicle processes distance and heading information to compute the change in north-south and east-west distance since initialization. Initialization is by officer action at a number of predefined points in the city. Dispatcher

Table 2. Characteristics of Example AVL Systems

Item	Model City		
	Small	Medium	Large
A. DEAD RECKONING USING VEHICLE ODOMETER – COMPASS **Technique Accuracy: 68 meters (224 ft) at 95%**			
System accuracy (meters)	68	68	100
Vehicle polling interval	0.2	2	4.6
Number of RF channels required (two frequencies per channel)	1	1	4
Number of dispatcher display devices	2	4	20
Number of city map sectors	1	10	100
System cost including 1 year maintenance – see Section 5.2 (thousands of dollars)	371	726	3,733
B. RF PROXIMITY USING SIGNPOST TRANSMITTERS **Technique Accuracy: 344 meters (1200 ft) at 95%**			
System accuracy (meters)	344	344	344
Number of signpost transmitters	117	1,167	11,667
Signpost density (posts per sq. mi.)	30	30	30
Vehicle polling interval (seconds)	0.2	2	4.6
Number of RF channels required (two frequencies per channel)	1	1	4
Number of dispatcher display devices	2	4	20
Number of city map sectors	1	10	100
System cost including 1 year maintenance – see Section 5.2 (thousands of dollars)	372	882	4,880
C. RADIOLOCATION USING PULSE TIME-OF-ARRIVAL **Technique Accuracy: 100 meters (328 ft) at 95%**			
System accuracy (meters)	100	100	100
Number of transmitter sites	1	1	2
Number of receiver sites	4	6	22
Number of calibration sites	1	3	11
Number of wideband RF channels required	1	1	1
Number of dispatcher display devices	2	4	20
Number of city map sectors	1	10	100
System cost including 1 year maintenance – see Section 5.2 (thousands of dollars)	459	776	3,614

action to reinitialize the computer may be required if the distance traveled between officer reinitializations is sufficiently large. The base station computer, in addition to having city map data, maintains each vehicle's position relative to some coordinate system, based on the changes in position reported by each vehicle. It also compares each vehicle's position to a city roadway and corrects that position to lie on the roadway. The computer controls the polling sequence for interrogation of in-service vehicles.

RF Proximity

In this example, low power transmitters emitting a unique coded signal are installed at every third intersection and connected to utility power. The radius of coverage is such that any instrumented vehicle entering the intersection will reliably detect the coded signal. The vehicle AVL receiver interfaces with a standard FM mobile radio to transmit both the identification of the signpost passed and its vehicle identification. As mentioned previously, a commanded polling scheme will be assumed for network control of the vehicle to base data channel. The base computer translates the reported signpost identification code to an intersection coordinate and maintains current files on vehicle identification vs. location. In addition, the computer has street map data stored for CRT display and controls the polling sequence for vehicle data reporting.

Radio Navigation

A pulse time-of-arrival system is used as an example of a radiolocation technique. Each vehicle is equipped with a transponder which receives an RF pulse and retransmits a pulse after a fixed delay. A fixed base station emits the first pulse, and at least three fixed receiving sites receive the return pulse from the vehicles. By measuring the difference in arrival time at two fixed receiving sites, a hyperbolic path can be determined as described in Chapter 2. In this example, four receiving sites are used to receive each vehicle's emitted pulse in order to reduce the location errors caused by radio propagation multipath and weak signal levels. The location data in this AVL technique is accumulated at each of the fixed receiving sites. Telephone circuits are used to transfer the location data from the receiving locations to a central data processing site where the location calculations are made and each vehicle's location is determined relative to a city coordinate system. The computer has city map data stored for CRT display with the location data. To further reduce the computed location errors, fixed calibration sites are located throughout the city. These are equipped with transponders like those in the vehicles, but since their position is known, correction factors can be applied to the time difference measurements

4.2 Observations About Design Examples

The preceding design examples illustrate system design and costs for three AVL techniques. Several comments should be made regarding the choise of system design parameters.

The dead-reckoning system requires reinitialization. It is not reasonable to expect field-officer-initiated action for reinitialization. Some form of automatic reinitialization should be used, such as widely spaced signpost transmitters and vehicle receivers. Spacings such that a vehicle passes a signpost with high probability every several miles of travel can provide good automatic reinitialization. The cost for this added equipment has not been included in the estimates in Table 3 (Section 5.2).

Because of the low value of signpost density, the resultant accuracy of the RF proximity example is significantly poorer than the other examples. This could be improved with higher density spacing (see Figure 12) or with the use of an odometer. However, the difference in average response time between all the example systems is quite small, as is seen in Figure 8.

The costs for each of the three example systems are not vastly different for small and medium cities either in dollars or in number of radio channels. It is observed that the radiolocation system is most advantageous for a large city while the proximity system is the highest cost for a large city, due primarily to the large fixed site (signpost transmitter) costs.

The AVL display technique makes use of a computer-stored city map with vehicle locations displayed on CRT devices. This technique, although impressive as a showpiece and useful in dynamic tactical situations, is not the best human interface for day-to-day dispatching. For this purpose, a simple tabular display of closest several cars to an incident's address is sufficient. For maximum benefit, an AVL system should be used in conjunction with a computer-aided-dispatch system which maintains vehicle status and addresses of requests for police service. For every request for police service, a computer recommendation for dispatch can be presented to the dispatcher. For administrative purposes, a tabular display again should suffice, showing the location of several selected vehicles. Another disadvantage of the computer map is the cost of encoding a city map with street names into computer memory. This is a very time-consuming effort.

Commanded polling was selected as a radio network control technique for transmission of vehicle-derived data to a base station. For the small and medium sized cities, only one radio channel (two frequencies) is necessary. However, for the large city, the polling interval for 500 cars would be 18 seconds if all were assigned to one radio channel. This interval would seriously degrade the inherent accuracy of a good AVL system as seen in Figure 10. For this reason, the large city example uses 4 RF channels for data transmission in the dead-reckoning and proximity designs. If synchronous polling in place of commanded polling was used, better utilization of the radio channel could be achieved, reducing the requirement from 4 to 3 channels for the large city.

The computational requirements of all the three techniques are quite modest even for the large city. A minicomputer class of machine when coupled with a bulk memory such as magnetic discs, will provide the necessary computing and storage capability. The city map CRT display requires a large computer-to-CRT data transfer. To reduce this, the CRT type selected in the examples contains internal memory, so that only vehicle location data is transferred to the CRT.

It is also important to reduce the response time of the computer to dispatcher-requested changes in map displays and in the display of updated vehicle location information. For this reason, fixed head rotating magnetic discs are preferred over other types of memory because of their relatively fast access time to retrieve stored data. This is particularly important in the large city case where the number of different map sectors and dispatchers is large. A city with a large general purpose computer can readily use this type of machine to support the AVL system. The economy, reliability, computer response time, and system-growth projections need to be carefully reviewed in order to make the proper choice.

5. PLANNING GUIDELINES: PREPARING THE IMPLEMENTATION PLAN

The planner evaluating possible AVL systems for his law enforcement agency will need to prepare an implementation plan for the system he selects, because only by preparing such a plan can he identify and estimate all the costs associated with implementing a given system. He may want to prepare implementation plans for two or more alternative systems for purposes of comparison. The plan (or plans) not only serves to identify all the costs; it identifies and schedules all the activities that will be required to acquire the system and place it into full operation.

5.1 Plan Elements

The three basic steps in implementing an AVL system are: analyze and define the requirements; select a system design or configuration; and prepare the planning and implementation documents.

5.1.1 Requirements

The basic function of an AVL system is to locate vehicles in a dispersed fleet in such a manner as to increase the efficiency and safety of the fleet operations. In performing this function the AVL system must meet certain technical, operational, and economic requirements.

Technical requirements center primarily on the accuracy of the system. This requirement has been stated elsewhere as a measure of confidence in location measurements, e.g., "the AVL system shall locate the vehicles in the fleet to within 500 feet of the true location 95 percent of the time." This requirement applies to moving as well as stationary vehicles, and takes into consideration the buildup in uncertainty with time as a vehicle moves away from its last known position (a finite delay is incurred due to polling, computational, and display processing).

The interval between location interrogations is closely related to the system accuracy and can only be specified as a requirement if the speed distribution of the fleet is well known. For this reason the polling or interrogation interval should not be specified for accuracy purposes.

Radio frequency channel utilization and the method of interrogation or polling are primarily operational requirements. A systematic survey of the fleet will provide an overview of the location of all the vehicles but at the poorest accuracy that the system can provide. The use of multiple radio channels can improve this performance through a decrease in the polling interval. However, operational considerations might dictate that the selective polling technique based on vehicle identification or location codes is a better technique.

The technical and operational requirements for AVL systems are particularly difficult to establish with confidence owing to the lack of data. There is simply not enough experience with AVL systems because so few operational installations exist. This difficulty is common to all new technologies. Chapter 3 suggests some criteria for developing accuracy specifications.

5.1.2 Configuration Trade-offs

The primary area for trade-offs in almost all AVL systems is the number of RF communication channels. The licensed channels are probably the most valuable resource of the agency. One arrangement might be to share the AVL data channels with other digital communications so as to use the addressing of the vehicle displays for AVL interrogations, or to append AVL data to status change messages.

5.1.3 Planning Documents

The planning documents are essentially those required for any new system procurement and include an overall schedule containing (at least) the following line items:

(1) Precontract study.

(2) Procurement.

(3) Facility preparation.

(4) Installation and checkout of equipment and software.

(5) System demonstration and acceptance.

(6) Personnel training.

(7) Maintenance.

Other items which may be required in certain cases include;

(8) Obtaining FCC license.

(9) Local government agreements or multiuser agreements.

(10) Time-phased implementation (a portion of fleet or portion of city is implemented at one time).

A typical planning schedule is shown in Figure 13.

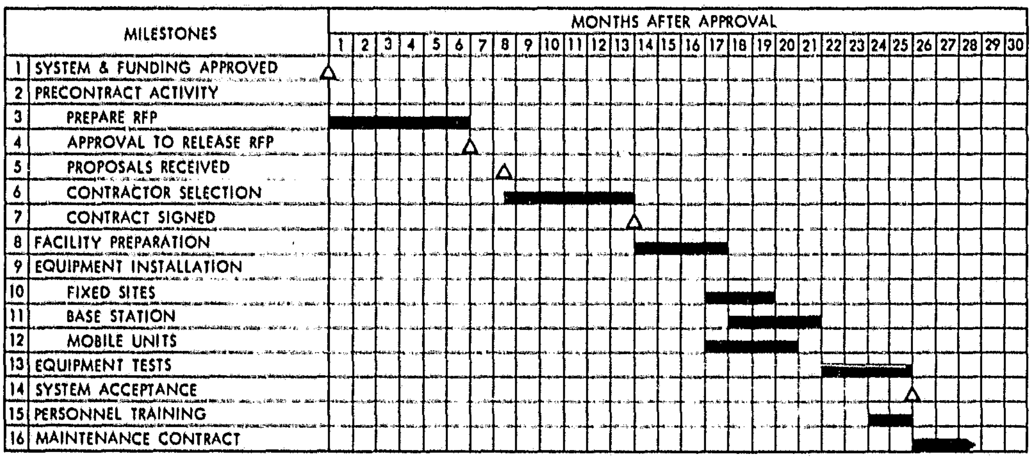

Fig. 13. Overall schedule of activities for radiolocation AVL example for medium size city

A funding plan should include, besides complete cost estimates, a breakdown of expenditures by fiscal year from the start of funding to completion of operational capability. Estimates for yearly maintenance should also be given. The elements in the funding plan generally include:

(1) The local agency program management office expenditures.

(2) Consulting or systems engineering support costs, if planned.

(3) Equipment and software procurement costs.

(4) Costs of facility acquisition and preparation.

(5) Cost of logistics (training, spare parts, maintenance).

A functional requirements document should be prepared which specifies what is wanted from the AVL system, defines the acceptable limits of performance, and defines interfaces with other systems. It is this document which forms the basis for a request-for-proposal to industry. Cost summaries for the example AVL systems are presented in Tables 3 - 5. The development of the cost estimates is discussed in the following sections.

5.2 Costs

5.2.1 Cost Elements

The costs of the AVL system can be apportioned among the various types of equipments common to all systems. These are vehicular, fixed sites, and base station costs. Vehicular equipment and fixed site costs can be considered as incremental costs, whereas the base station equipments, computer, communication interfaces, and displays are essentially one-time, front-end costs (unless leasing is used).

In addition to the equipment costs as such, there are the installation costs, which are rather straight-forward for the vehicles. Fixed-site equipment installation costs for signpost systems are also rather easy to estimate for the average installation. The more complex special-purpose fixed sites for radiolocation systems are somewhat harder to estimate because of the greater number of factors involved, such as power, rent, and data links.

Base station equipments are hard to estimate because of the large variety of computers, displays, communication interfaces, and existing facilities; a satisfactory estimate requires fairly detailed knowledge of the particular installation.

5.2.2 Continuing Costs

Maintenance costs of the vehicles will increase because of the addition of AVL equipment. This is brought about not only by the AVL system devices but by the interface equipment for vehicle communications.

Maintenance and replacement of proximity type fixed-site equipments is another ongoing cost. Maintenance of batteries and antennas and the repositioning of disturbed units will be needed as wear-out occurs and the performance of units installed in exposed locations degrades. Replacement of sealed coded units will necessitate documentation changes to reflect the fact that a location is now known by a different code.

Fixed sites for radiolocation systems will require more expensive maintenance as they require checkout at the site

Table 3. Cost Estimate for Dead-Reckoning AVL System

Item	Small City	Medium City	Large City
1. Vehicle costs			
Sensors $1,325 ea.	$ 13,250	$132,500	$1,325,000
Radio 1,045 ea.	10,450	104,500	1,045,000
	$ 23,700	$237,000	$2,370,000
2. Fixed site costs			
3. Base station costs			
Radio	9,000	9,000	36,000
Computer and software	150,000	210,000	480,000
Telephone line costs per year	1,000	1,400	7,200
	$160,000	$220,400	$ 523,200
4. Engineering	90,000	150,000	387,000
5. Program management	88,000	88,000	221,000
6. Maintenance costs per year	8,900	30,900	232,000
Total estimate including 1 year maintenance	$370,600	$726,300	$3,733,200

Table 4. Cost Estimate for RF Proximity AVL System

Item	Small City	Medium City	Large City
1. Vehicle costs			
Proximity receiver $ 215 ea.	$ 2,150	$ 21,500	$ 215,000
Radio $1045 ea.	10,450	104,500	1,045,000
	$ 12,600	$126,000	$1,260,000
2. Fixed site costs			
Signpost transmitters $ 275 ea.	32,082	320,820	2,291,666
3. Base station costs			
Radio	9,000	9,000	36,000
Computer and software	130,000	150,000	420,000
Telephone lines costs per year	1,000	1,400	7,200
	$140,000	$160,400	$ 463,200
4. Engineering	90,000	150,000	387,000
5. Program management	88,000	88,000	221,000
6. Maintenance costs per year	9,650	36,400	257,000
Total estimate including 1 year maintenance	$372,332	$881,620	$4,879,866

Table 5. Cost Estimate for Radiolocation AVL System

Item		Small City		Medium City		Large City	
1. Vehicle costs							
Transponder	$1435 ea.		$ 14,350		$143,500		$1,435,000
2. Fixed site costs							
Receiver sites	$25,000 ea.	$100,000		$150,000		$550,000	
Transmitter sites	$ 6,000 ea.	6,000		6,000		12,000	
Calibration sites	$ 2,035 ea.	2,035		6,105		22,385	
			$108,035		$162,105		$ 584,385
3. Base station							
Computer and software		130,000		190,000		450,000	
Telephone line costs per year		14,500		21,750		88,900	
			144,500		$211,750		$ 538,900
4. Engineering			90,000		185,000		500,000
5. Program management			88,000		88,000		221,000
6. Maintenance costs per year			14,250		40,500		312,000
Total estimate including 1 year maintenance			$459,135		$830,855		$3,591,285

rather than at a shop or manufacturer. The larger fixed-site equipments generally utilize very accurate timekeeping devices which may need frequent calibration.

Base station equipment maintenance is quite similar to that required for computer installations, and the techniques and costs are fairly well established for the various computers. Similarly, the costs of displays and interface maintenance are well established.

In all of the cases, maintenance can be accomplished either by the local agency or by service agreements with the suppliers.

5.2.3 Other Cost Elements

Costs can be shared if there are other users of the AVL system. Although this is a simple concept, one agency must have overall responsibility for operation of the system. This agency is placed in the role of a service agency, which is not its primary responsibility in the case of a police department. If another city or private agency is assigned responsibility for system operation, its highest priority user, the police department, may not receive the 24 hour per day, 7 day per week service that it requires.

5.3 Other Implementation Activities

5.3.1 Installation

The installation plan can take two general forms: either a phased plan or a "turnkey" plan, wherein the entire AVL system is put into service at once. Obviously, the former is the lower risk approach but has possibly higher costs.

The phased plan has some variations that are technique dependent. Dead-reckoning or existing radiolocation navigation techniques require virtually no fixed sites: wide area coverage is available from the start. The vehicle installations can be started with a single car provided and necessary radio and base station computation equipment and display(s) are available.

Proximity system equipments can be installed incrementally, one area of the city at a time. If the vehicles assigned to this area are equipped at the same time, an orderly plan can be established whereby the areas of highest priority are provided with the AVL service first.

Special purpose radiolocation techniques, because of the relatively wide dispersion of the fixed sites, can provide a substantial area of coverage with the first installations. An incremental installation of vehicle equipment can spread costs over a longer period.

In all cases the base equipment should be installed and checked out first to test the vehicular and fixed site installations. The installation schedule is dictated by funding, delivery schedule, and operational considerations.

5.3.2 Continuing Operation

Once the AVL system is declared operational, continual maintenance service must be furnished. Personnel training and upgrading of the equipments and procedures must also be considered.

6. PLANNING GUIDELINES: COST BENEFITS ANALYSIS

In Chapter 2 we described applications of AVL for law enforcement. From these we can identify a set of benefits that can be expected to follow from the implementation of an AVL system:

(1) Shorter response time to citizen calls.

(2) Better deployment of forces during tactical situations.

(3) Improved officer safety.

(4) Better supervisory control.

(5) Use in patrol effectiveness studies.

(6) Use in surveillance situations.

(7) Multiple user benefits.

(8) Reduced voice channel congestion.

(9) Improved communications security.

Obviously, few of these benefits, and certainly not the most important of them, can be expressed in dollar terms. Of the benefits listed, items 1 and possibly 4 can be measured in terms of dollars. The others can be evaluated only in qualitative terms.

The simulation results of Doering (Ref. 4) for the City of Orlando, Florida, showed that 34 patrol cars with AVL could have a travel time to an incident equivalent to that of 35.8 patrol cars without AVL. This was based on an AVL system with an accuracy of 800 feet, and a policy of dispatching the closest vehicle. This is a 5 percent saving in the number of patrol cars due to reduced response time. This percent reduction is less if we take into consideration time to service incidents, time for prevent patrol, station time, and other nonproductive times. To what degree the patrol force can be reduced is not really known; there is insufficient field experience and no comprehensive analysis of an operating system to predict this.

Figure 8, which is based on the work of Larson (Ref. 2), predicts a 6 - 12 percent reduction in average travel time. Other work by Larson in Boston (Ref. 5) measured the time taken for the various steps in the police dispatch and incident service functions. Based on these results, the travel time is at most an average of 18 percent of a field unit's active time, and decreases as the amount of prevent patrol time increases. Applying a 6 - 12 percent reduction to 18 percent of a field unit's time results in at most a 1 to 2 percent reduction in the number of patrol cars.

Research using AVL techniques should be performed to identify areas in which supervisory control could be improved. There are no reported studies on this. Depending on the base from which one applies better supervisory control, the resultant savings might be anywhere from zero to in excess of 10 percent.

For the purpose of the cost benefits analysis, we will use a 3 percent reduction in number of patrol cars resulting from the increased efficiency of both closest car dispatching and better supervision. This reduction appears valid for the range of AVL accuracies exhibited by the three example systems of Chapter 4.

The benefit analysis will assume a 5-year life for the AVL system. The equipment life should be longer than 5 years, but there will be new developments in AVL equipments and operating techniques so that system modifications might be anticipated within 5 years. Each car saved is worth $150,000 annually based on one-man cars and the salaries of officers to man it 24 hours per day. Costs have not been adjusted for the effects of inflation over the 5-year period.

Tables 6 through 8 show estimated 5-year savings, costs, and net cost benefits of two example AVL systems for three model cities. Neither system is justified in the small city on the basis of cost savings alone. In the medium and large cities, positive cost-benefit ratios are shown, with the dead reckoning example providing the largest benefit.

While cost-benefit ratios are an important criterion in evaluating potential system alternatives, the planner should be

Table 6. Estimated 5-Year Savings with AVL

	Model City		
	Small	Medium	Large
Number of units on patrol without AVL	5	50	500
Number of patrol units saved with AVL	0.15	1.5	15
Annual savings at $150,000 per patrol unit (dollars)	22,500	225,000	2,250,000
Five-year savings (dollars)	112,500	1,125,000	11,250,000

Table 7. AVL System 5-Year Costs

Item	Model City		
	Small	Medium	Large
A. DEAD RECKONING			
Fixed cost (dollars)	360,700	694,000	3,494,000
Recurring cost (dollars)			
Per year	9,900	32,300	239,200
Per 5 years	49,500	161,500	1,196,000
Total 5-year cost	410,200	855,500	4,690,000
B. RADIOLOCATION			
Fixed cost (dollars)	430,400	768,600	3,190,400
Recurring cost (dollars)			
Per year	28,800	62,300	400,900
Per 5 years	143,800	311,300	2,004,500
Total 5-year cost	574,100	1,080,000	5,195,000

concerned with other factors:

(1) System accuracy.

(2) Radio channel requirements.

(3) Field officer and dispatcher support required.

Table 8. Net 5-Year AVL Cost Benefits for Three Model Cities

AVL Example	Model City		
	Small	Medium	Large
Dead reckoning (dollars)	-297,700	269,500	6,560,000
Radiolocation (dollars)	-461,635	39,034	6,032,730

(4) Interface with other police systems.

(5) System expandability.

As an example of the importance of these other factors, we showed that the dead-reckoning system example provided the largest cost-benefit ratio. However, this system also required frequent (20 - 40 mile) reinitialization by officer and dispatcher manual actions. This should never be required by a system; all reinitialization should be automatic.

For those benefits for which cost values cannot be assigned, the relative degree to which competing AVL systems provide the benefits can be established. These, as well as performance factors and cost, are then weighted in terms of relative importance. The result gives an overall ranking of competing AVL systems in terms of benefits as perceived by the user.

REFERENCES

1. *Report on Police*, National Advisory Commission on Criminal Justice Standards and Goals, 1973.

2. Larson, R. C., *Urban Police Patrol Analysis*, MIT Press, 1972.

3. *Task Force Report: Science and Technology*. A Report to the President's Commission on Law Enforcement and Administration of Justice, Sept. 1974.

4. Doering, R. D., *Vehicle Locator Feasibility Study*, Final Report Submitted to Governor's Conference on Criminal Justice, Tallahassee, Florida. Mar. 1974.

5. Larson, R. C., *Operational Study of Police Response System*, Technical Report No. 26, Operations Research Center, Massachusetts Institute of Technology, 1967.

6. Riter, S., Jones, W. B. Jr., and Dozier, H., *Speeding the Deployment of Emergency Vehicles*, IEEE Spectrum, Dec. 1973.

7. *1974 Carnahan and International Crime Countermeasures Conference Proceedings, University of Kentucky*, Aug. 1974.

8. Fey, R. L., *Automatic Vehicle Location Techniques for Law Enforcement Use*, LESP-RPT-0205. 00, U.S. Department of Justice, Sept. 1974.

9. Hansen, G. R., *Automatic Vehicle Monitoring System Study*. Jet Propulsion Laboratory, Pasadena, Calif. (in preparation).

APPENDIX A

PARTIAL LIST OF AVL SYSTEM VENDORS

This list is intended to provide a source for additional information regarding AVL systems. Those organizations known to have AVL systems in current use or who have been active in test programs are listed. It is inevitable that the list is incomplete and out-of-date as soon as it is published.

The Boeing Company Wichita Division 3801 South Oliver Wichita, Kansas 67210 (316) 687-2408	Dead-reckoning system using odometer and compass.
E-Systems, Inc. P.O. Box 6118 Dallas, Texas 75222 Attn: Digicom (214) 272-0515	Dead-reckoning system using odometer and compass aided with radio frequency signpost transmitters.
Hazeltine Corp. Cuba Hill Road Greenlawn, New York 11740 Attn: Marketing Dept. (516) 261-7000	Trilateration system using a wideband radio frequency pulse technique with vehicle transponders.
Hoffman Electronics Corp. 4323 Arden Drive El Monte, California 91734 (213) 442-0123	Proximity system using radio frequency signpost transmitters in Citizens Band at 27 MHz.
Motorola, Inc. Communications Division 1301 East Algonquin Road Schaumburg, Illinois 60172 Attn: Mobile Data Products (312) 397-1000	Dead-reckoning system using odometer and compass aided with radio frequency signpost transmitters.
Novatek, Inc. 79 R. Terrace Hall Avenue Burlington, Massachusetts 01803 (617) 272-6230	Proximity system using buried magnet arrays aided by vehicle distance and turn sensing.

APPENDIX B

DESCRIPTION OF THE FLAIR SYSTEM (FLEET LOCATION AND INFORMATION REPORTING)*

1. System Description

Automatic Vehicle Monitoring System

FLAIR is a vehicle location and information system which automatically updates each FLAIR-equipped vehicle's precise location and corresponding status and presents this information to police dispatchers in the command and control center. The location and status of all FLAIR-equipped vehicles in service is continuously available for subsequent dynamic display to each dispatcher on selectable map areas which are presented in a color TV format. Each dispatcher has a continuously updated picture of the deployment of the mobile police force, and thus complete command and control of the FLAIR-equipped vehicles under his responsibility.

The basic system combines dead-reckoning and map-matching techniques that develop accurate vehicle location information. Vehicle heading and distance data are formatted with coded messages in the vehicle data processor and transmitted in digital form to the base equipment during a time slot designated for each vehicle.

Data received at the radio frequency data terminal (RFDT) is decoded and transferred to a digital minicomputer. Navigational computations are made in the minicomputer and this data, along with message information and control signals, are transferred to the control console/display in the form of colored symbols on a map and message information in the form of colored symbols on a map and message information in the form of numerics. Requests can be sent from the control console to have the computer select information to be displayed or to perform specified functions. A diagram of the system is shown in Figure B-1. The control console/display units are shown in Figure B-2.

The system has a capacity of 200 police vehicles per UHF mobile frequency.

Operational Features

The FLAIR system provides a number of features to give the dispatcher rapid and detailed information on individual vehicle location and officer/vehicle status. The symbol representing the assigned vehicle on the TV map display is modified to indicate the officer's status, e.g., out-of-service, available for call, low priority call, high priority call or emergency. A specific officer/vehicle can be located by entering either the assigned officer's call number or the vehicle's FLAIR number into the computer by using console controls. An open-square tracking symbol is then displayed on the TV map around the displayed vehicle location.

One important FLAIR application is locating an officer who has signaled an emergency and dispatching the nearest officers to assist him. The dispatcher receives an indication of the emergency situation by an audible alarm, the vehicle number with an "E" symbol appearing at the top of the message column, and modification of the vehicle's displayed symbol. The four closest available vehicles are displayed in the message column in order of proximity by a single action of the dispatcher. If the dispatcher desires that more than four vehicles be sent to assist an officer in trouble, the call numbers of other vehicles can be displayed on the TV map by actuating the appropriate console control switch. Any combination of five categorized groups of vehicles, such as detective or patrol, can be selected for display.

To service an incident, the dispatcher designates the point of interest with the cursor control. The call numbers of the four available officers in their order of proximity to the location are displayed in the message column on the dispatcher's display. By depressing a number switch, identification of all officers (call numbers) are displayed on the TV map adjacent to their vehicle symbols. Since the dispatcher can view the continuous movement of all field forces, communication security can be provided by directing the officer to the incident by route rather than incident address. The dispatcher can avoid assignments to an incident requiring the officer to cross major barriers such as rivers and freeways as well as assist officers in finding an address. The display of the location and availability of vehicles gives the dispatcher the capability to direct vehicles assisting in a high-speed chase.

The coded message panel, shown in Figure B-3, enables the vehicle officer to transmit up to 99 two-digit codes and also indicate when emergency assistance is required. Digital code transmission assures that these messages from the field are received by the dispatcher even though voice channel communication may be congested.

The FLAIR system can improve many facets of police response to an incident by giving the dispatcher full knowledge of the location and status of all the field forces. Situations such as road blocks, civil disturbances, community disaster and burglar or robbery alarms require that a number

*By permission of The Boeing Co., Wichita, Kansas.

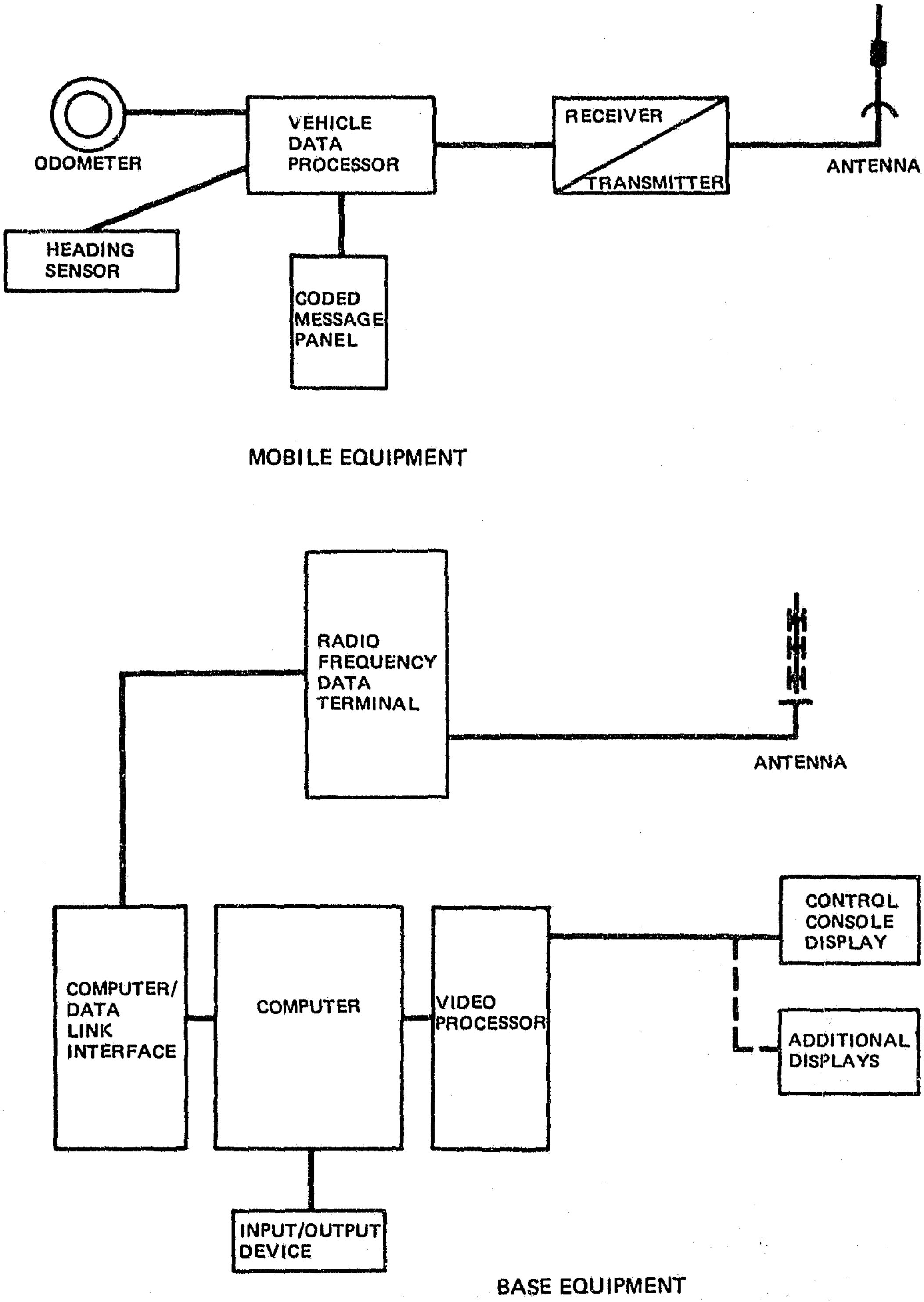

Fig. B-1. FLAIR system block diagram

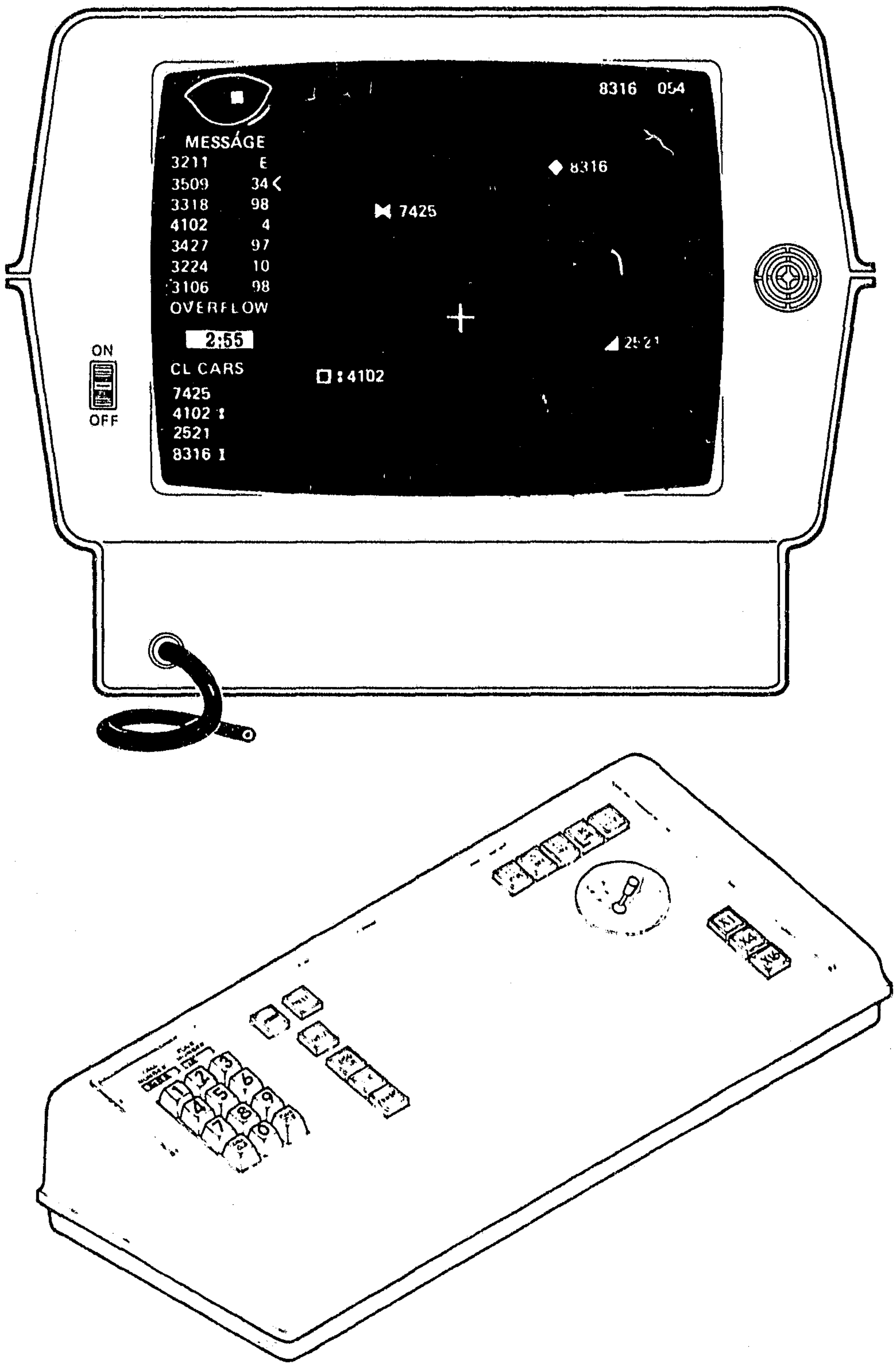

Fig. B-2. Typical control console/display

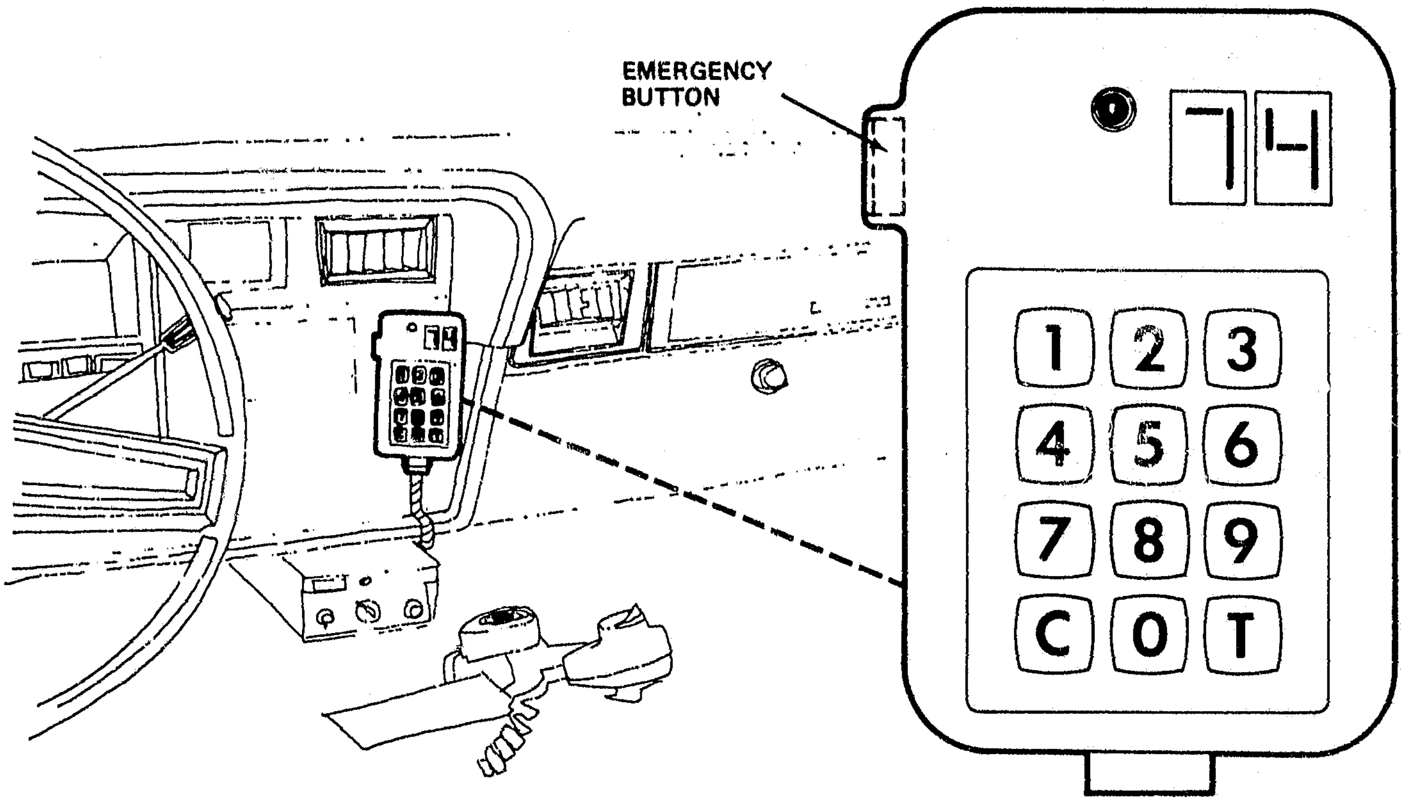

Fig. B-3. Typical coded message panel

of officers be dispatched in a timely manner to precise locations. FLAIR provides the information to accomplish these operations effectively. For crimes such as armed robberies and burglaries in progress, the dispatcher has the information so that appropriate officers can be selected for quick response. Accurate, up-to-date information on location of the responding officers gives the dispatcher the capability to place patrol units around the scene of the crime quickly.

Digital Communications Technique

The Boeing FLAIR system employs a dedicated radio data link between the base equipment and the mobile equipment. It is not designed to share time or equipment with an existing police voice radio complex.

General Electric MASTR Progress Line 70 watt transmitter-receivers with supplemental receivers (one for each additional set of vehicles exceeding a multiple of 200) are modified for use as the base equipment RF data terminals. RCA Series 700 FM transceivers (with 20 watt power output) are modified for the mobile data radios. Modifications consist of disabling circuits normally used for voice and adding devices and circuits to enable pulse and digital signals to be processed.

The radio equipment described above operates in the UHF band, on frequencies specifically allocated for Automatic Vehicle Monitoring service. The two frequencies will be a normal channel (base-mobile pair) in the 450 MHz to 470 MHz region. Additional receivers are in the same band.

FLAIR-equipped vehicles report their location and status information in a time division multiplex mode. All vehicles are synchronized to a master base station via reception of a transmitted signature sync signal which resets their precision internal reference oscillators approximately once per second. The vehicle equipment counts down to their assigned time slots and reports the necessary coded information in approximately 5.1 milliseconds. Information content from each vehicle contains 20 bits of heading, distance, and situation data prefaced by a correlation code used by the base station to clock in received data.

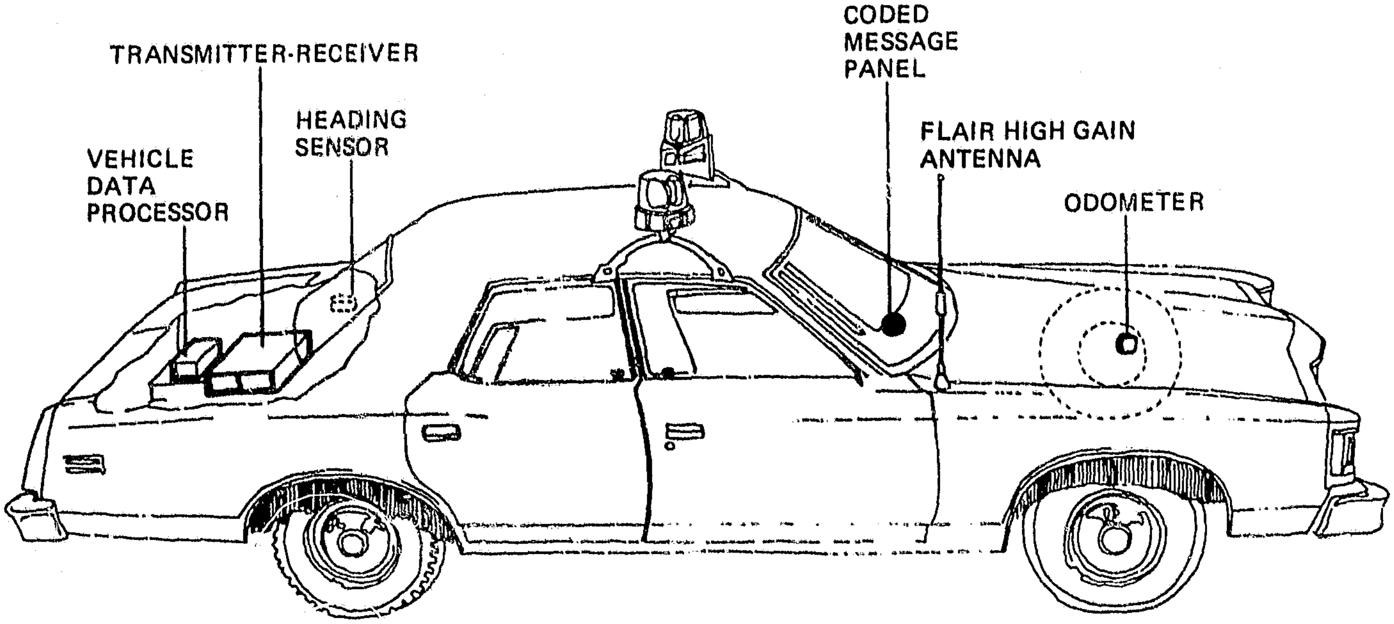

Fig. B-4. Typical mobile equipment installation

Mobile Equipments

The mobile equipment develops the self-contained dead-reckoning navigation and vehicle/officer information. All components are solid-state. A typical mobile equipment installation is shown in Figure B-4.

The heading sensor determines the vehicle's instantaneous magnetic heading with a resolution of 2.8 degrees. The odometer determines distance traveled to an accuracy of ± 0.5 percent. Both functions are automatic and do not require adjustments from the vehicle officer. The coded message panel is used to initiate digital messages. The data processor multiplexes the heading, distance traveled and the coded message for transmission in the proper time slot.

Officer/vehicle messages may be reported by transmission of a digital coded message (see Figure B-3). Any desired message may be assigned to any two-digit code (99 possible). To transmit, the two digits are entered on the coded message panel and the momentary $\boxed{T}$ switch is depressed. Numerical indicators on the panel identify which message is being transmitted. Transmission continues until the $\boxed{T}$ switch is again depressed, the clear switch depressed, or the vehicle's ignition is turned off. The message number is displayed at the dispatcher's display (except for certain select codes) until the transmission is stopped or the dispatcher removes it.

When the emergency switch, located on the coded message panel, is depressed it causes an audible sound at the dispatcher console, a high priority vehicle symbol on the display map, and an E beside the vehicle call number appears at the top of the message column, indicating immediate assistance is required by the vehicle officer.

Base Equipments

The base equipment includes all FLAIR system components required to process the location and vehicle/officer message data received from the mobile equipment and to display the processed data to the dispatcher. The equipment includes a radio frequency data terminal (RFDT) and antenna, computer/data link interface unit (CDLIU), a minicomputer and peripherals, a video processor, and control console/display. Remote RFDTs may also be used to obtain the required coverage.

The RFDT and antenna provides the base portion of the UHF (450-470 MHz) two-frequency data link (200-car system) over which synchronization and data are transmitted. A modified General Electric 70-watt RF transmitter/receiver and Boeing signal processing circuitry provides the required functions to maintain the time division multiplex data link between the mobile equipment and the base equipment.

The CDLIU interfaces the RFDT and the FLAIR computer. Remote RFDTs may be coupled to the CDLIU by modems and telephone lines which have specifically defined characteristics.

The CDLIU provides system synchronization, converts data to computer format and generates data-ready pulses.

The computer system includes memory and dedicated processing capability for tracking mobile units and operating the displays. The video processor provides the link to transfer digital data and control signals between the computer system and the control console/display.

The computer provides the control, analysis, input/output, and other computational capabilities required to track vehicles, decode status information, and present the resulting data to the dispatcher on the control console/display. A fixed head magnetic disc is used for vehicle tracking and a moving head magnetic disc supplies storage for system and program files, scratch areas, and display maps. The teletypewriter (TTY), card reader, and line printer provide the programmer interface to the computer.

The computer, a Varian 73, is a system-oriented general-purpose minicomputer, which has the following features:

- 16 bit word length.
- 65,536 words of dual ported magnetic core memory.
- Memory cycle time of less than 1 microsecond.
- Floating point firmware.
- Direct memory access with data rates up to 1,220,000 words per second.
- 24 levels of priority interrupts.

The two random access magnetic disc units supply the computer with sufficient high-speed mass storage to support the real-time tracking operations. The programmer interfaces the computer through a teletypewriter, card reader, and a line printer. The TTY can print a 72-character line at a rate of 10 characters per second using either rolled or stacked paper. The line printer is a Centronics Model 306. It is a 5 by 7 dot matrix impact printer with a speed of 100 characters per second. The Centronics 306 prints 80 characters per line and 6 lines per inch on standard 80-column sprocketed paper. The Varian card reader has a continuous reading rate of 300 cards per minute.

The Video processor contains circuitry to interface the control console/display with the computer. Additional circuit boards are added to the video processor for each control console/display. Each video processor can handle as many as seven control console/displays.

The display consists of a modified TV receiver employing a standard 30-frame per second, 525-line TV raster format. The console controls enable the dispatcher to select all or part of the city street map in any of three scales and view the symbols indicating FLAIR equipped vehicle locations. Elements of the display are the map, vehicle message, closest available vehicles (to an electronically generated cursor), a city outline map, and time-of-day (digital format). Five different symbols are available to identify various categories of vehicles.

The functions of the console/display controls (shown in Figures B-5, B-6, and B-7) include:

- Scale select switches.

  These switches enable the dispatcher to select any of three map scales stored by the computer up to X16 magnification (X1, X4, X16). The system may be altered to provide up to five map scales if desired.

- Officer category switches

  The dispatcher may select any one of any combination of five officer categories (category and title to be established by the Police Department) to appear on the display. Each category has a unique identifying sumbol on the X4 and X16 scales. The X1 scale displays a single smaller symbol to reduce congestion.

- Locate Switch.

  Entering a call number or FLAIR number on the keyboard and depressing this switch selects the proper display map and the location of the vehicle is indicated by an open-square tracking symbol. Any vehicle location can be displayed regardless of status. As the located vehicle moves near the boundary of the displayed map area, the map is automatically translated to reposition the vehicle near the new map center. Upon return of the switch to its original position, the open square tracking symbol no longer surrounds the vehicle symbol and the cross-hair cursor is displayed at the map center.

- Cursor control.

  The cursor control enables the dispatcher to position a cross-hair cursor to select desired positions of the city map for viewing.

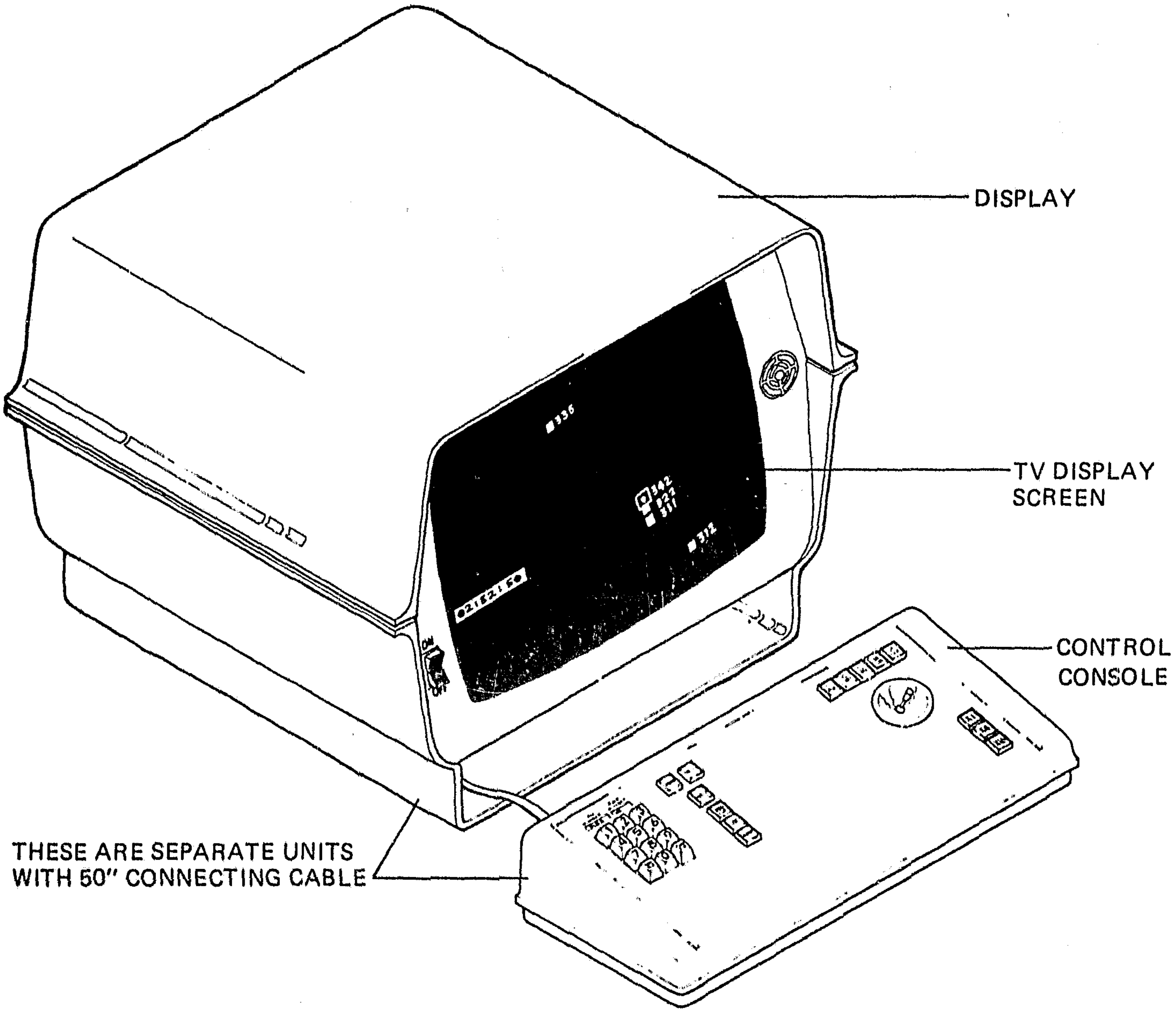

Fig. B-5. Typical control console/display

- Number switch.

  Depressing this control switch causes the assigned identification number, or FLAIR time slot number for unassigned cars to be presented on the display at each vehicle's location on the X4 and X16 map scales.

- Initialize switch.

  This switch is usec in conjunction with the cursor control and keyboard to initialize vehicle location following equipment installation and to again correctly initialize if error develops in vehicle position.

  Using the cursor control, the appropriate map is selected and the cross-hair cursor located at the vehicle's true location, the call number or FLAIR number is entered through the keyboard and the initialize switch depressed.

- Assign switch.

  The assign switch is used with the keyboard to assign an officer call number to the vehicle FLAIR

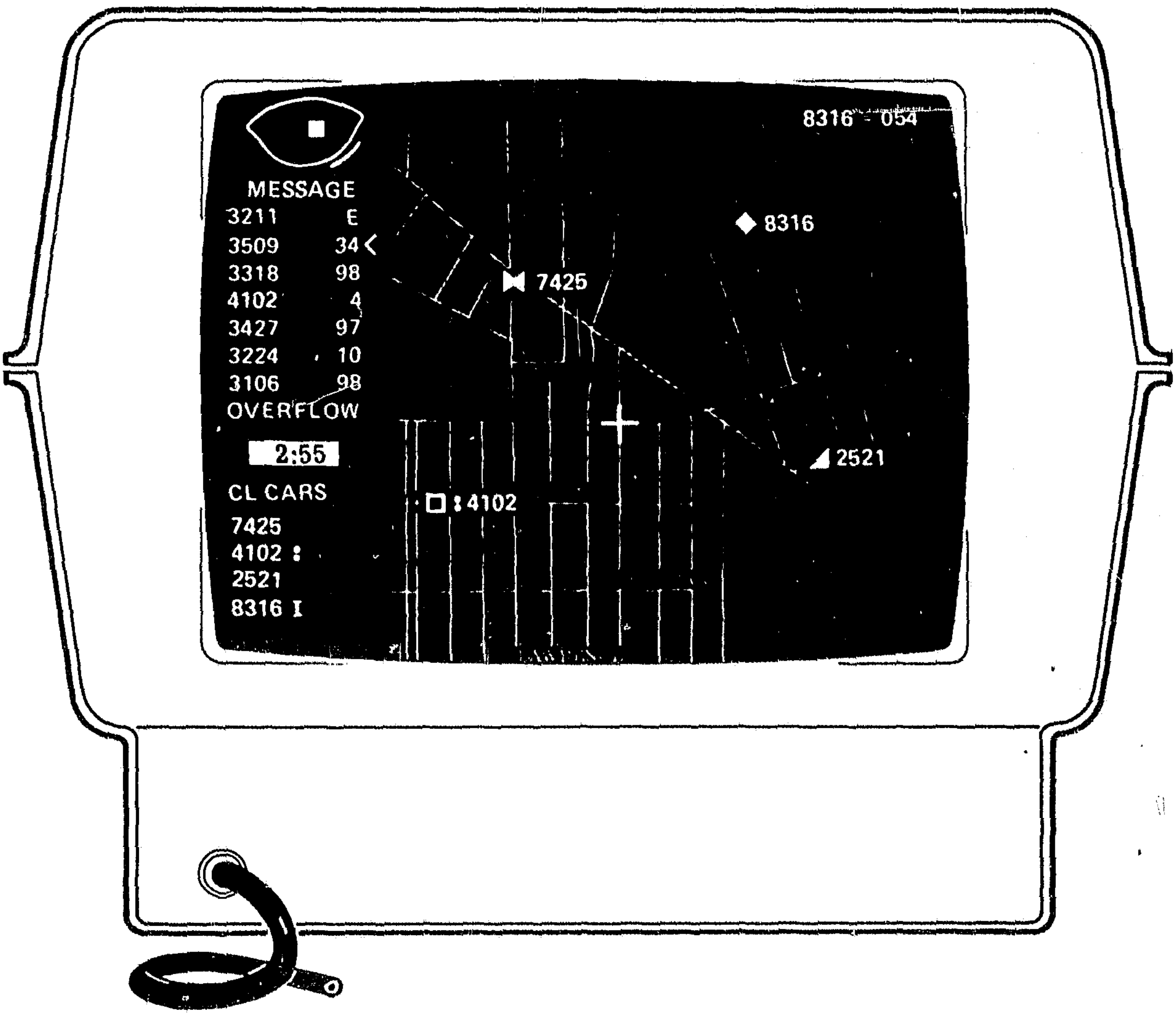

Fig. B-6. Typical display presentation

number by entering the number into the computer. It is also used to assign an individual vehicle to a district. Digital messages are sent to the appropriate display.

- Message clear switch.

This switch enables the dispatcher to clear the officer call number and message indication from the message column on the display. The officer call number is entered on the keyboard; and by depressing the message clear switch, the information is removed from the display. This action is also used when taking a vehicle/officer out of service and when removing verification symbols. (A verification symbol, V, is displayed next to the call number when the computer determines that there is a high probability that a vehicle needs to be initialized.) Most messages appearing on the display are removed by the vehicle officer.

2. System Performance

System Response Time

The FLAIR system meets the dispatcher requirement for near real-time information for vehicle locations, digital codes, emergency signals and provides the capability to rapidly select new information for display. The FLAIR system response time for each of these factors is discussed below.

System response time factors include the system report period of 1.22 seconds, telephone line delay from base station

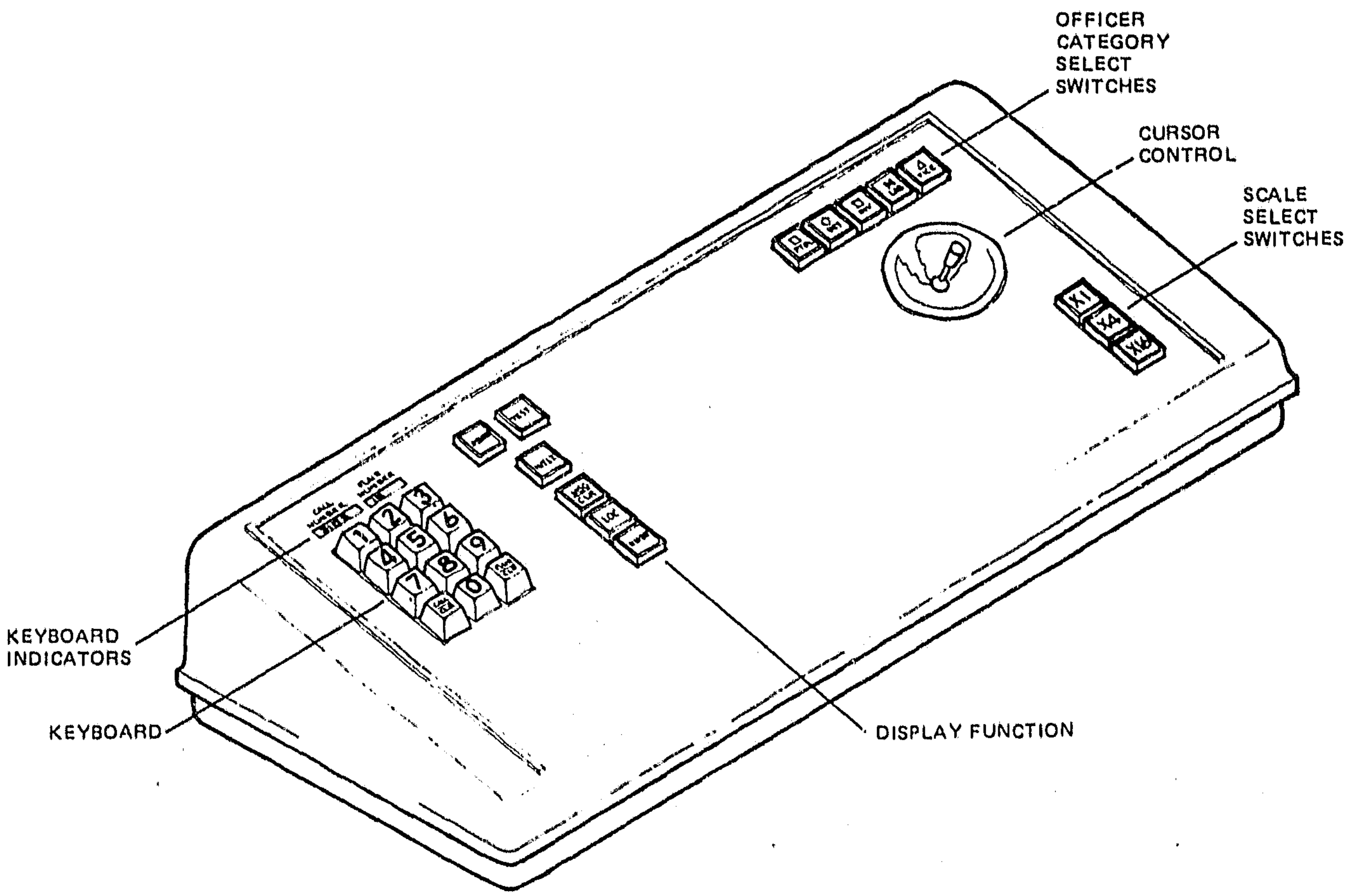

Fig. B-7. Typical dispatcher's control console

to dispatch area where computer and control console are located and the transfer and manipulation of digital information in the computer. Since all digital information is held in an input buffer until the information from the next reporting period is received, the response time for data transmission from the vehicle to display at the dispatcher's console will always exceed 2.43 seconds. The single digit emergency signal is not displayed until two consecutive emergency codes are received in order to minimize the possibility of transmission errors. Two-digit codes require two reporting periods for transmission and these codes are not displayed until two consecutive signals are received.

Table B-1 summarizes the system response times for presentation of information on the dispatcher's CRT after data or code entry at the vehicle. The maximum response time is developed by assuming the worst case condition where data or code entry at the vehicle occurs at the beginning of the reporting period, thereby adding 1.22 seconds to the total response time, i.e., from data or code entry at vehicle to display on CRT. The response time for the CRT display of information requested by the dispatcher Console Service Request is also listed in the table.

Accuracy

The accuracy of the FLAIR system was measured in St. Louis by making 12 test runs over a 19.2-mile course which included a wide variety of driving conditions and street patterns. The average error measured during these runs was 72 feet. The test route is shown in Figure B-8.

Table B-1. System Response Time (seconds)

	Nominal	Maximum (50 vehicles)
Display of vehicle location	2.4	3.7
Emergency signal display	3.6	4.9
Digital code display	6.1	7.3
Console service request	2.3	3.5

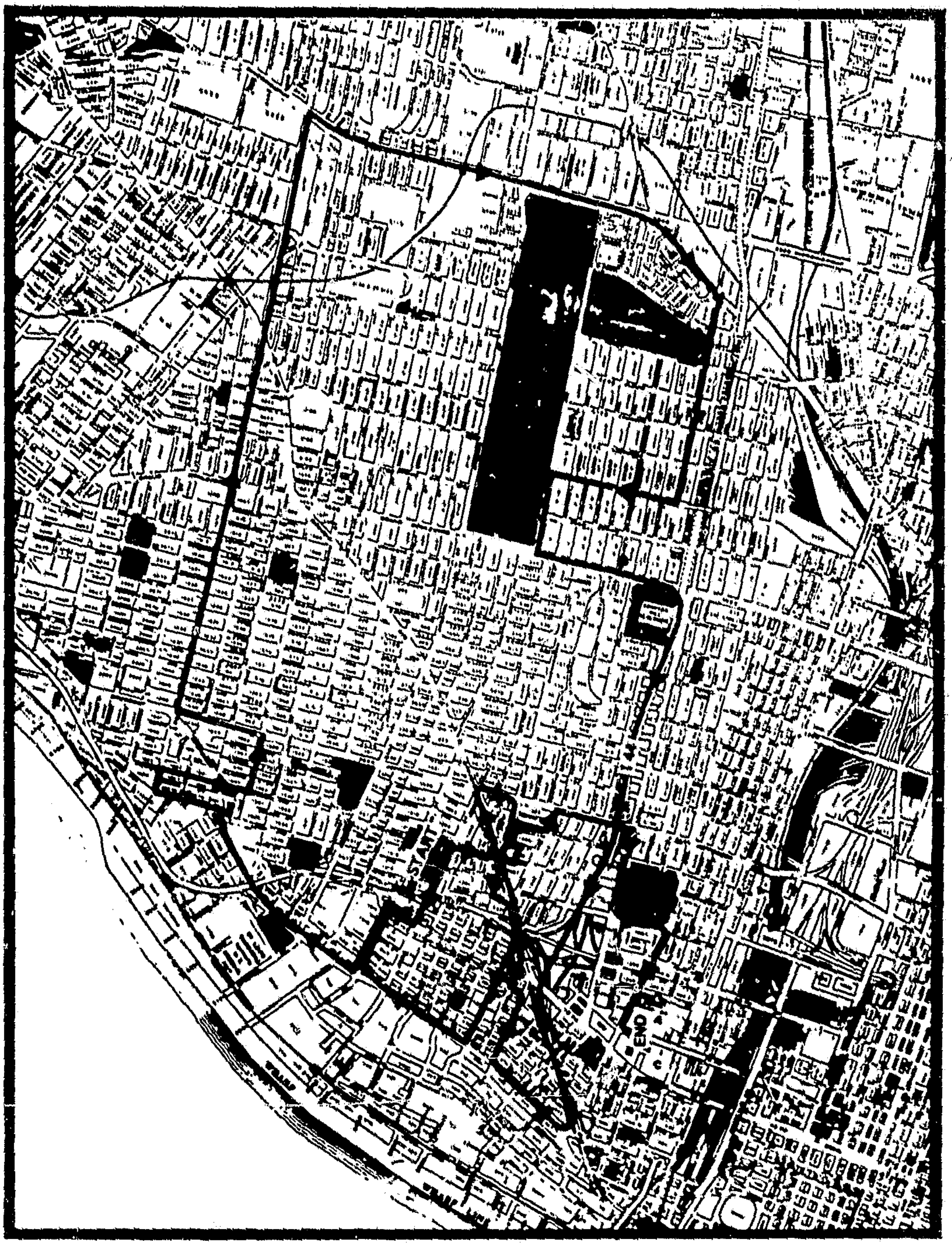

Fig. B-8. St. Louis FLAIR tracking test route

Driving speed varied from slow alley driving to high speed interstate highway conditions. Long straight runs, many turns, backup, and engine "on-off" were included. Straight, curved, narrow, and wide streets and streets intersecting at small angles were also included in the test.

The average system error of FLAIR during the 12 test runs with no dispatcher initializations was 72 feet. It was found that without initialization the cars were on the correct street 95.7 percent of the distance traveled. When the car was on the correct street, tracking errors presented no operational problems. When the vehicle was displayed on the correct street, it was displayed with an error equal to or less than one-half block for 96.4 percent of the distance traveled. In summary, the vehicle was displayed with an error of less than one-half block, 92.7 percent of the distance driven including travel on incorrect streets, and was displayed with less than 224 feet error, 95 percent of the distance traveled.

The errors of two of the test runs were large compared to the average of the 12 runs. In an operational situation, these runs would have been initialized by the dispatcher when the "Vs" appeared in the status column. The computer is programmed to present a vehicle's call number and the letter "V" in the status column anytime the system updates the vehicle to a street by an amount greater than a prescribed value. The presentation of the "V" is an indication to the dispatcher that the vehicle's location should be verified. Two of the runs were replayed and initialized soon after the "V" occurred. The average system error for the 12 runs with two initializations was 56 feet. It was found that the cars were on the correct street 97.3 percent of the distance traveled. For 4.3 percent of the distance traveled, the car was on the correct street and displayed with an error greater than one-half block. In summary, the cars were displayed with error of less than one-half block, 93.7 percent of the distance traveled and were displayed with less than 178 feet error, 95 percent of the distance traveled. It was estimated by analysis that if two additional cars had been replayed and initialized immediately upon the appearance of a "V" an additional three times, the error in the displayed location of the vehicles would have been reduced to less than 150 feet, 95 percent of the distance covered. A detailed description of the method of calculation and detailed results are in Boeing Document D246-2006, "Pilot Program Final Report" dated 9 May 1975.

Several system changes resulting from the St. Louis pilot program are being implemented to improve the system tracking accuracy. These improvements include transmitting additional bits of distance and heading information and making use of a greater portion of the available mapping information. Resolution of the distance information is improved from approximately 25 feet to 6 feet by transmitting two additional bits from the mobile vehicle. Heading resolution is improved from 11.25 degrees to 2.8 degrees by transmitting two additional bits of heading information. Also, several hardware improvements have been made which will further reduce the acceptance of bad data.

☆ U.S. GOVERNMENT PRINTING OFFICE : 1979 O—281-380 (4546)

END